NASA/CR–2011-217082

# Parametric Modeling of the Safety Effects of NextGen Terminal Maneuvering Area Conflict Scenarios

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April 2011

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Prepared for Langley Research Center
under Contract NNLO6AA05B

April 2011

## Acknowledgments

We would like to thank the technical teams within Honeywell and Sensis that assisted in conducting the work under this program. In particular, we wish to acknowledge John Sorensen's substantial contribution to our understanding of innovations in approach procedures. We would also like to thank Denise Jones and Randy Bailey for their continuous engagement and guidance in helping us perform the work.



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# 1. Executive Summary

Emerging Next Generation Air Transportation System (NextGen) operational concepts represent a radically different approach to air traffic management and as a result, a dramatic shift in the tasks, roles, and responsibilities for the flight crew to ensure a safe, sustainable air transportation system. One of the key challenges associated with the NextGen involves automated surface management systems that utilize dynamic algorithms to calculate the most efficient movement of all surface traffic to increase efficiency. Fortunately, advanced surveillance, flight management, communication, navigation, and crew-vehicle interface equipage holds the promise of enabling more efficient and safer surface operations. Yet increases in pilot roles and responsibilities, higher information load, quicker paced operations, smaller safety margins, and more complex operations could lead to erosion of the proactive safety layers that enable present-day operations. It will be vital to retain and even improve upon these proactive safety layers for NextGen.

Limited research to date has been conducted on concepts and issues associated with conflict detection and resolution (CD&R) in a NextGen environment, particularly in the Terminal Maneuvering Area (TMA) and on the surface. Further, 4-dimensional (4-D) terminal area operational concepts proposed for NextGen are being built upon present-day operations that are not free of risk. Consequently, the goal of this work was to analytically identify and quantify the issues, challenges, technical hurdles, and pilot-vehicle interface issues associated with CD&R in emerging operational concepts for NextGen TMA, including surface operations. In order to assess the overall effectiveness of CD&R in a future environment, the study addressed many different factors at a high level, with the goal of creating a credible performance analysis framework and identifying potential issues for further research.

More specifically, the following objectives were addressed:

- Develop first-order modeling techniques to quantitatively address the broadest possible set of factors affecting the achievable safety benefits in future NextGen environments.
- Apply these models to estimate the overall effectiveness of NextGen TMA CD&R as a function of critical parameters using different combinations of:
    - Representative conflict scenarios for low-altitude, runway, and taxiway conflicts, and
    - Alternative models of end-state NextGen equipage and ground assets.
- Identify Crew Vehicle Interface (CVI) technologies, hurdles, challenges & research and development (R&D) needs.

To this end, the work entailed analytical and trade studies focused on modeling the achievable safety benefits of different CD&R strategies and concepts in the current and future airport environment. The initial activities defined equipage baselines and assumptions in terms of performance characteristics and capabilities of relevant surveillance and alerting systems such as Automatic Dependent Surveillance – Broadcast (ADS-B) and Airport Surface Detection Equipment – Model X (ASDE-X). Finally, assumptions were made concerning NextGen terminal area procedures, CVI and pilot alerting concepts, pilot performance, and overall CD&R requirements and constraints. NextGen documentation provides a vision for a variety of operational, aircraft, and ground infrastructure changes that could potentially increase capacity and safety. Yet it is uncertain which of these envisioned changes will be realized and how quickly. In order to specify a variety of values for the modeling analyses performed here, many operational assumptions and performance predictions had to be made. Some of these were simply agreed upon based on the expertise of the National Aeronautics and Space Administration (NASA), Honeywell, and Sensis team members, while others were derived from review and analysis of data and previous documentation. Many assumptions and performance predictions were ultimately simplified for practicality in order to make a broad modeling analysis possible.

These assumptions were used as the framework for identifying a small set of alternative NextGen environments that reflected end-states based on different CD&R strategies and concepts. Based on this framework, CD&R parametric models were developed with a limited set of representative major equipage configurations and surveillance quality values. Five conflict scenarios were developed along with metrics for the safety impact of the assumed technologies in order to exercise the models and produce preliminary safety benefit predictions.

In addition, CVI and pilot performance enhancements and potential issues were analyzed based on review of envisioned NextGen operations, expected equipage advances, and human factors expertise. These analyses led to development of a simple pilot response time model used in the parametric modeling analysis. However, significant uncertainty in pilot performance issues in a NextGen environment make it likely that the response time model used was an over-simplification and many of the pilot performance issues and degree of benefit of CVI advances will need to be explored empirically.

The major findings of the study are listed below.

Developing a quantitative analytical model for overall CD&R effectiveness in a future environment that addresses variations in surveillance quality, CD&R equipage, encounter parameters, and flight crew response time is challenging, but feasible.

The assumption that CD&R performance is limited primarily by kinematic state estimation and prediction, rather than correctly classifying the encounter, is important to the study conclusions. This assumption can be assured by the provision of appropriate air-ground data links for information on critical operational transitions, particularly intended runway, acceleration, and turns.

CD&R effectiveness should be modeled against a representative ensemble of encounters, rather than a small number of point scenarios, because the chance of successful response may depend critically on the time at which a mistake is made. Systematic or random (Monte Carlo) variation of the relative timing of encounters is essential to assess effectiveness.

The sometimes-critical dependence of the conflict encounter outcome on flight crew response time demonstrates the need to consider the combined effect of situation awareness (SA), workload, indications, and multi-level alerts on outcomes, and to validate the response time models assumed for the study.

The size of the margin between an acceptable operation and an encounter with collision risk is critical to the ability to achieve an acceptable nuisance alert rate while maintaining safety. Low nuisance alert rates are achievable under the assumption that occasional alerts for procedural violations of those safety margins are acceptable (i.e., not considered nuisance alerts). If operational safety margins are not much larger than the uncertainty in the CD&R prediction, either compromised detection or high nuisance alerts are inevitable. Therefore, if new NextGen procedures assume reductions in these margins, the CD&R capabilities assumed might not be achievable.

Global Positioning System (GPS)-derived ADS-B velocity should be used in CD&R systems if it is as accurate as promised, but will only change alert effectiveness significantly where the margin between acceptable and unsafe behavior is relatively small and dependent on velocity measurement. In particular, it was found that using this measurement improved safety in the overtaking-taxi scenario, but not in the runway crossing or intersecting arrivals scenarios.

The combination of object size uncertainty and residual error in ADS-B position in a multipath environment limits the ability to detect low-speed and static conflict situations (such as stationary targets slightly over the hold line). However, if reasonable position margins are maintained, the collision risk from undetected violations of this type is small.

Often the largest contribution to the uncertainty in predictions of future state is the assumed behavior of an aircraft after an operational transition (for example, how hard an arriver will brake after landing). When these uncertainties dominate, improvements in surveillance precision offer no benefit. To the extent that future behavior can be predicted more precisely, the alerting system may become more effective.

The example results of perturbation analysis, which quantified the high-level performance impact of changes to key parameters such as median response time and surveillance position error, showed that the analytical model developed could be useful in making technology investment decisions.

Based on the simple models used for the benefits of passive situation awareness (provided by a Cockpit Display of Traffic Information (CDTI)), there was a substantial difference in overall safety capability between assumed NextGen environments. Under these models, investing in either comprehensive aircraft-based alerting or a ground-based alerting system would reduce the collision risk by multiple orders of magnitude compared to NextGen relying primarily on situation awareness. The degree to which initial lapses will be prevented by improved situation awareness is unknown; this factor, combined with increased demands in the NextGen environment, will determine whether the assumed NextGen baseline is significantly safer than current operations.

The assumed situational awareness benefit of cockpit displays such as CDTI strongly impacted the difference in safety between NextGen environments. Further research is needed to measure the extent to which these technologies help pilots to avoid or recover from lapses.

In scenarios requiring a prompt evasive maneuver to resolve a conflict, ground-based alerting was less effective due to the latency in communication between the aircraft and the alerting system. However, if a significant fraction of aircraft does not equip an on-board system, a ground-based system that issues alerts to all aircraft may offer adequate safety. Also, in some scenarios, the ground-based system may be able to coordinate alerts and resolution advisories among multiple aircraft to a degree that on-board systems cannot.

The modeled safety benefits of CD&R depend on the ability to develop crew-vehicle interfaces that facilitate quick execution of the appropriate reaction, matching or exceeding the assumed response time distributions under realistic conditions. Integrating the capability for alerts with displays and indications that direct attention to the significant threats before they become acute should be a primary research focus.

Among the scenarios examined, performance depended most strongly on the level of equipage for the overtaking-taxi scenario, because taxiway CD&R was assumed to be provided only by high-end on-board or ground-based alerting systems. For runway collision hazards, partial equipage offered adequate benefits because runway alerting was provided at a lower level of equipage.

# 2. Introduction

By 2025, United States (U.S.) air traffic is predicted to increase 3-fold, yet the current air traffic system may not be able to accommodate this growth. In response to this challenge, a consortium of industry, academia and government agencies has proposed a revolutionary new concept for U.S. aviation operations, termed the Next Generation Air Transportation System or "NextGen" (e.g., FAA, 2008; FAA, 2009 (a); JPDO, 2007; JPDO, 2008; NextGen Mid-Term Implementation Task Force, 2009). Emerging NextGen operational concepts represent a radically different approach to air traffic management and as a result, a dramatic shift in the tasks, roles, and responsibilities for the flight crew to ensure a safe, sustainable air transportation system.

One of the key challenges associated with the NextGen involves automated surface management systems that utilize dynamic algorithms to calculate the most efficient movement of all surface traffic to increase

efficiency. Pilots will be required to comply with 4-D taxi clearances, dictating that aircraft arrive at specific locations within specific time windows. Further, pilots may be responsible for separation from other aircraft during these operations regardless of visibility conditions.

Proactive safety layers enable present-day operations. These layers include automation to manage, assist, and even conduct these procedures and operations. In today's operations, a significant layer of CD&R capability is provided by the Traffic Alert and Collision Avoidance System (TCAS). TCAS has been developed and improved for over 15 years and has been very effective in reducing or eliminating airborne collisions.

NextGen operational concepts are beginning to emerge to meet the projected air traffic service demands. It will be vital to retain and even improve upon these proactive safety layers for NextGen. Limited research to date has been conducted on concepts and issues associated with CD&R in a NextGen environment, particularly in the TMA and on the surface. 4-D terminal area operations concepts proposed for NextGen are being built upon present-day operations that are already problematic. In the four year period between 2005 and 2008, 3,496 runway incursion events were reported, which is a rate of more than two runway incursion events per day (FAA, 2009 (b)). The present-day statistics and events are cause enough for alarm but, without proactive counter-measures, the increase in air traffic forecasted under NextGen and using novel 4-D operating concepts could potentially result in catastrophic increases in runway and taxiway incursion accidents.

Consequently, the goal of this work was to analytically identify and quantify the issues, challenges, technical hurdles, and pilot-vehicle interface issues associated with CD&R in emerging operational concepts for NextGen TMA, including surface operations. This was a high level, "first pass" analysis intended primarily to identify potential issues for further research.

# 3. Study Objectives and Approach

The overall goal of this work was to analytically identify and quantify safety issues associated with CD&R in emerging operational concepts for NextGen TMAs. More specifically, the following objectives were addressed:

- Analyze the projected safety level for NextGen TMA CD&R with:
    - Alternative NextGen TMA CD&R scenarios.
    - Different surveillance equipage and their associated qualities, including ADS-B equipage, and different flight deck alerting assumptions.
- Identify CVI technologies, hurdles, challenges & R&D needs.

To this end, the work entailed analytical and trade studies focused on modeling the achievable safety benefits of different CD&R strategies and concepts in the current and future airport environment. The initial activities defined equipage baselines and assumptions in terms of performance characteristics and capabilities of relevant surveillance and alerting systems such as TCAS, ADS-B, and ASDE-X. Further, future avionics and relevant airborne and ground system performance and capabilities were identified based on assumptions concerning likely extensions to current baselines. Finally, assumptions were made concerning NextGen terminal area procedures, CVI and flight deck alerting concepts, pilot performance, and overall CD&R requirements and constraints.

These equipage baselines, predicted extensions of capabilities, and operational environment assumptions were used as the framework for analytical trade studies aimed at identifying a small set of alternative NextGen environments that reflected end-states based on different CD&R strategies and concepts. Based on the trades, iterated assumptions, and system performance predictions, CD&R parametric models were developed with a limited set of representative major equipage configurations and surveillance quality values. Five conflict scenarios were developed along with metrics for the safety impact of the assumed

technologies in order to exercise the models and produce preliminary safety benefit predictions. The scope of the analysis was limited in the following ways to keep it within programmatic constraints:

- The primary safety metric was the fraction of potential hazards where the assumed CD&R systems would be effective in preventing collision, rather than an absolute accident rate. [Assuming an error that could result in a collision occurs, the probability of automatically generating an alert from any of the assumed CD&R systems in time to successfully initiate corrective action was estimated under the assumption that no other corrective action was taken. This approach avoided the complexity of inferring the rates of errors and corrective actions in the current environment and extrapolating those rates to a future environment that is not fully defined].
- Metrics were applied to "end-state" NextGen environments, not transitional partial equipage environments, for easier technology comparison.
- CD&R functions were considered as an independent system for safety assurance, and, therefore, independent of the technology implemented for Equivalent Visual Operations (EVO) and Trajectory Based Operations (TBO).

Only algorithms essential to predicting the performance limits of future CD&R, rather than a complete CD&R function were modeled.

The tasks that comprised this effort are summarized below.

**Task 1.** Characterize the set of airport operations in the assumed NextGen environment and identify the baseline systems that would provide safety assurance. The focus was on parametric changes to runway operations (e.g., faster, denser traffic) rather than hypothesizing specific NextGen-possible operational procedures.

**Task 2.** Define analysis assumptions, metrics, and scenarios. Metrics focused on feasibility of effective alerting, rather than a predicted accident rate requiring guesswork on underlying human error rates by pilots or controllers.

**Task 3.** Conduct preliminary trade studies of alternative CD&R strategies, methodologies and equipage and select alternatives to the baseline. For each strategy, a mature equipage end state was assumed with uniform adoption within each aircraft class of the equipage needed to support the CD&R strategy. The trade studies focused on the capability of the assumed CD&R technology to prevent collisions, rather than creating a rationale for the assumed environment. [The eventual NextGen environment will depend on a combination of economic, safety, and policy factors that are beyond the scope of the current study.]

**Task 4.** Develop parametric models to evaluate the effect on safety of the interaction of assumed CD&R-relevant equipage, communication, surveillance, alerting and display systems, and pilot performance. Parametric models focused on the coupled problems of defining rational alert criteria and estimating achievable sensitivity. Estimation of time clearance was the central problem, and outcomes were based on simple response time models for human performance.

**Task 5.** Conduct parametric analyses. The models addressed representative airport environments rather than the entire range of possible scenarios. Techniques for scaling the Monte Carlo analyses to feasible sizes were developed after determining sensitivities in parametric model studies.

# 4. Background

In this section, background information is presented on the architecture, technology, and procedures that affect the future NextGen environment. The specific, simplified models used for the study are presented in Section 5.

## 4.1 NextGen Air Traffic Management (ATM)

NextGen documentation provides a vision for a variety of operational, aircraft, and ground infrastructure changes that could potentially increase capacity and safety (e.g. see JPDO, 2007). Yet it is uncertain which of these envisioned changes will be realized and how quickly. In order to specify a variety of values for the modeling analyses performed here, many assumptions and performance predictions were made. Some of these were simply agreed to be based on the expertise of NASA, Honeywell, and Sensis team members, while others were derived from review and analysis of data and previous documentation (referred to here as the "trade studies"). Some of the key assumptions used here, which either directly or indirectly affected the modeling input, are listed below. Many assumptions and performance predictions were ultimately simplified for practicality in order to make a broad modeling analysis possible.

### Key Assumptions

General assumptions were:

- Procedures for precise TBO will enable reduced separations (especially for approaches to parallel runways) for properly equipped aircraft and airports.
- Role of CD&R equipage, in conjunction with new operational procedures, will be to provide an underlying safety layer in the TMA for such operations in zero or low visibility (with pilot visual detection of conflicts secondary).
- "Eyes out" will still be required for ground operation (either use of HUD/HMD or one pilot head down, one head up).
- Incentives for new equipage will increase the pace of introduction relative to historical norms.
- Ground-based surveillance services will be widely available.
- Ground stations for Automatic Dependent Surveillance- Rebroadcast (ADS-R) will be provided to support the dual-link concept. Under the dual-link concept, some aircraft transmit and receive ADS-B on one physical link (the 1090 MHz Extended Squitter or 1090ES protocol) while other aircraft (expected to be the typical General Aviation user) transmit and receive using a different physical link (Universal Access Transceiver or UAT, expected to use 978 MHz). The ground stations broadcast ADS-R on the appropriate link to provide mutual awareness between differently-equipped National Airspace System (NAS) users.
- ASDE-X or another ground surveillance system such as Low-Cost Ground Surveillance (LCGS) will provide Traffic Information Services-Broadcast (TIS-B) services for non-ADS-B equipped traffic at some airports.
- Environment will include mix of aircraft/equipage capabilities:
  - Retrofit costs make complete upgrade unlikely.
  - Some aircraft may use audio-only situation awareness (SA) and alerting.
- EVO will be manifested as sustained operations at peak capacity.
- Pilots will retain final authority for conflict resolution (no automated maneuvers).

Simplifying assumptions for CD&R-relevant equipage levels were:

- Limit aircraft classes to 3 major classes:
  - New transport aircraft.
  - Retrofitted transport aircraft.
  - Non-transport.
- Limit combinations of surveillance to:

  - TCAS or successor (potentially fusing ADS-B).
  - ADS-B on-board: Minimum capability of Out or Out+In assumed.
  - Ground surveillance: Either ASDE-X (fusing Multilateration (MLAT), Surface Movement Radar (SMR), and other sensors) or none.
- Crew interface for CD&R: moving map with ownship or CDTI with traffic.
- Limit conflict detection capability alternatives according to source:
  - On-board: non-traffic (risks unrelated to traffic, such as wrong runway or taxi route), basic runway (common high-speed runway collision risks), or comprehensive (collision risks in terminal airspace and surface movement area).
  - Ground uplink: comprehensive.

## 4.2 Surveillance

For the purpose of evaluating CD&R, surveillance is the set of all sources of real-time information on the identity, position, velocity, and other dynamic characteristics of objects in the terminal area. Therefore, processing to fuse data from multiple surveillance systems or to pre-process the data for better accuracy effectively becomes part of the surveillance input to CD&R. In the interests of keeping the study results general, the models characterized the accuracy of the surveillance data without specifying the source of the measurement. The results of research into the anticipated accuracy of NextGen surveillance are given below.

Under NextGen, ADS-B "Out" is expected to be provided by aircraft in the terminal areas of towered airports. Over the next decade, commercial aircraft are expected to equip with ADS-B "In" and "Out" in increasing numbers, supporting enhanced operating capabilities including merging and spacing, CDTI, TCAS, and other functions. Additionally, some aircraft will have Head-Up Displays (HUD) using Enhanced Vision Systems (EVS) with infrared or millimeter wave radars to allow operations in low visibility conditions. New landing systems such as the Global Navigation Satellite System Landing System (GNSS) and ground surveillance such as ASDE-X will also be widely available. However, aircraft will equip at different rates, and aircraft and airports with advanced surveillance capabilities will have to handle potential conflicts with less-equipped aircraft.

The ASDE-X system is a ground surveillance system providing accurate position, velocity, and identification (via transponder code) of all aircraft. ASDE-X also provides conflict detection for a specified set of runway scenarios. ASDE-X fused track reports are based on the combination of all sources of information on an object, typically including both SMR primary radar reports and multilateration reports on Mode-S or Air Traffic Control Radar Beacon (ATCRB) System transponder replies. ASDE-X also receives ADS-B transmissions from equipped aircraft, which are becoming more common each year but still are fewer than 10% of all flights at most U.S. airports. (Equipage decisions by individual carriers can rapidly change that number for particular airports.) ASDE-X is scheduled for deployment at the 35 largest U.S. airports. The LCGS system is an alternative to ASDE-X and is currently in prototype development. LCGS is expected to be deployed at smaller airports with significant need to manage surface traffic.

The precision of surveillance and positioning equipage is critical to the overall modeling results of CD&R safety levels. Some of the key assumptions about surveillance and positioning accuracy[1] are described below.

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[1] The performance models for GPS receivers are based on consultation with Brian Schipper, a subject matter expert at Honeywell [personal communication.]

- The types of errors for GPS receivers fall into four main categories:
  - Bias (e.g., constellation position or differential-GPS (DGPS) ground station survey errors),
  - White noise (e.g., measurement noise),
  - Lightly-damped Gauss-Markov noise (e.g., signal multipath), and
  - Heavily-damped Gauss-Markov noise (e.g., atmospheric conditions interference).
- The assumed variance for each GPS error source depends on:
  - The types of receiver, as higher quality receivers generally have less noise and other errors; for example, a receiver may use narrower correlation windows to reduce multipath.
  - Environment of operation (multipath is generally worse on the ground than in the air).
  - Availability and use of DGPS, as DGPS eliminates bias but may increase multipath susceptibility.
- Special considerations for GPS error modeling include:
  - The multipath period may be as long as 100 sec for static ground conditions, decreasing as trajectory dynamics increase.
  - A dual frequency receiver can eliminate ionospheric error contribution.
  - DGPS eliminates all atmospheric errors for receivers within approximately 10 km of the base station but its effectiveness is reduced during strong ionospheric scintillation.
- ADS-B surveillance will focus on position accuracy:
  - Reported accuracy category (Navigation Accuracy Category (NAC)-7, -8, …).
  - Distinguish reported from internal accuracy (ownship knows internal).
  - Address important departures from simple white-noise Gaussian error models, including e.g., time-correlated errors and position outliers.

A parametric model of GPS accuracy in the NextGen environment, assumed to represent the best case accuracy for ownship position and velocity, was developed with variants for each major category of aircraft assumed for the NextGen environment. The range of expected GPS accuracy is presented in Table 1 and the basis for aircraft categorization is discussed further in Section 5.1.3.

Models were developed for ground surveillance accuracy as well, based on the ASDE-X system capability. Ground surveillance accuracy was modeled to establish a baseline for ATC conflict detection and resolution capability without new equipage and also to characterize the quality of information potentially available (directly or as source of fused surveillance) to the flight deck via TIS-B and ADS-R).

The ASDE-X internal system position accuracy is based on the smoothed output of fusion tracker which processes contributions from multilateration, surface radar, Airport Surveillance Radar (ASR), and ADS-B from equipped aircraft. The typical multilateration position specified accuracy (transponder-centered) is 6 m (1-sigma), but anomalies such as multipath may occur. Position accuracy for a surface movement radar measurement is computed based on the centroid of the object, which is usually over-resolved (appearing in multiple range-azimuth cells.)

The ability to convey position report accuracy is to some extent limited by the communications format. It has been assumed for this study that ground-based fusion tracker position estimates used for ADS-R will likely conform to the DO-260A standard (RTCA, 2003). It is possible that in the future, services such as TIS-B could use a different format with better precision for reporting accuracy (as opposed to the quantization incurred in the DO-260A format by using NAC values as conservative accuracy bounds).

For this study, the conflict detection performance model was based on single-update report accuracy (e.g., position or position/velocity) augmented with a simple model for achievable predicted future state accuracy, rather than a fully developed tracking process. The same model formulation was used for all sources, but the model accuracy parameters varied with the assumed source.

**Table 1. Range of GPS Accuracy Expected in NextGen Environment**

| | | **Aircraft Category in NextGen Environment** | | |
|---|---|---|---|---|
| **Error model parameter** | **Units** | **Transport - New** | **Transport - Retrofit** | **General Aviation (Low-cost)** |
| **GPS position errors:** | | | | |
| Bias | m | 3, 1, 5 | 3, 1, 5 | 3, 1, 5 |
| White noise | m | 0.5, 0.1, 2 | 0.5, 0.1, 2 | 1, 0.5, 3 |
| Fast drift (lightly-damped) | m | 2, 0.1, 10 | 2, 0.1, 10 | 5, 1, 20 |
| Slow drift (heavily-damped) | m | 0.1 | 0.1 | 0.1 |
| Fast drift period | sec | 1.5, 0.5, 3 | 1.5, 0.5, 3 | 1.5, 0.5, 3 |
| **GPS velocity errors:** | | | | |
| White noise | m/s | 0.03, 0.01, 0.10 | 0.03, 0.01, 0.10 | 0.1, 0.01, 0.30 |
| Note: The three values in each cell are estimates of the nominal, minimum, and maximum value expected for the given aircraft class under normal airborne conditions. | | | | |

## 4.3 Crew-Vehicle Interface (CVI)

Human error is a causal or contributing factor in a large majority of aviation accidents and incidents. Hence, when analyzing potential safety issues related to CD&R in a NextGen TMA environment, a key element of the analysis is flight crew performance and the state-of-the-art of flight deck CVI supporting the flight crew. This section describes some of the NextGen TMA operations, equipage, human factors issues, and potential NextGen TMA CD&R safety impacts related specifically to CVI and flight crew performance. In the Conclusions and Recommendations section, this topic is revisited through discussion of outcomes of the modeling analysis that have CVI-related safety implications.

### 4.3.1 Potential CVI-relevant NextGen TMA Operational Changes

There are a variety of envisioned NextGen TMA operations that could impact CVI requirements and pilot performance. Key operations that could have significant impact on CVI and flight crew performance are listed below.

1. *Equivalent Visual Operations (EVO)*. EVO, which implies that aircraft could operate under visual flight rules (VFR) in zero-zero conditions, would require that flight crews perform CD&R actions without the ability to visually acquire the potentially conflicting aircraft, using natural vision. This would mean that ATM, ground and aircraft surveillance systems, positioning data, and the CVI displays (including EVS) and alerts are the primary source of CD&R information and would need to meet more stringent reliability and integrity levels. Without natural visual data to confirm or deny the

presence of a potential conflict, required surveillance system "miss" and false/nuisance alarm rates will need to be re-evaluated.

2. *Faster paced, higher density operations*. Increasing airport throughput means faster paced and higher density operations compared to today, especially in low visibility conditions. Ground operations are already a very busy time for flight crews, and increases in time pressure along with smaller margins of error mean that the CVI will need to provide critical information in a time-critical manner without inundating pilots with too much information or distracting them with too many alerts or annunciations.
3. *More brittle operations*. With time-based operations and smaller margins for separation assurance, any deviation such as a missed Required Time of Arrival (RTA) at an intersection, or a perturbation such as an aircraft needing to stop or slow down to solve some aircraft problem, may create more rippling effects in terms of disruptions to overall traffic flow and airport operations than in today's operations. This brittleness, if it were to occur, could create even more pressure on flight crews to hurry, accept clearances that are difficult to meet, and try to multitask during taxi operations when they should be focused exclusively on maneuvering the aircraft between the runway and the gate. In order to mitigate these brittleness effects, the CVI will need to supply pilots with better situation awareness, help them manage workload, and provide more strategic and pro-active information about potential problems in executing issued clearances.
4. *Mixed CVI equipage*. NextGen will clearly need to accommodate mixed levels of CVI equipage. Even though the intent is to incentivize equipage levels which enable new higher capacity operations, not all operators will be able to equip to the same levels or at the same pace for economic as well as other reasons. In terms of TMA CD&R, this will mean that better CVI-equipped aircraft will need to account for potential conflicts with less equipped aircraft where certain assumptions about the accuracy and timeliness of pilot responses based on higher levels of equipage will not be valid.
5. *Different levels of airport surveillance infrastructure*. Utilization of new landing systems such as Ground-based Augmentation System (GBAS) and broadcast of ground surveillance information such as ASDE-X to the flight deck should provide heightened levels of TMA CD&R performance. But CVI design will need to accommodate integration of ground-based surveillance and aircraft surveillance to minimize confusion, and pilots will need to be able to clearly differentiate between airports where the additional CD&R infrastructure is available and those where it is not.
6. *Different pilot roles and responsibilities*. Generally, the roles and responsibilities of pilots will be different, and probably more demanding. Without mitigation, this will likely increase workload, which can delay response times and increase errors. The CVI challenge is presenting information to pilots that supports the new roles and responsibilities without inundating them with too much information or too many attention-getting alerts and indications, and keeping the information and tasks simple.
7. *More highly automated and more complex operations*. Use of automation will continue to increase, requiring pilots to monitor more systems and increase awareness of automation behavior. More automation complexity could increase the problem of lack of mode awareness and automation surprises. The CVI challenge is providing proper information content that allows pilots to accurately assess the state, mode, behavior, and implications of automated system operation and consequent flight status.

### 4.3.2 NextGen CVI Equipage

The overall aircraft equipage assumptions for the analyses are provided in a subsequent section. However, a more detailed summary in terms of potential CVI equipage for NextGen is provided here. CVI equipage can play an important role in maintaining or improving safety in a NextGen TMA environment.

There are many CVI products and concepts under development that are aimed at improving flight crew SA, especially as it relates to TMA CD&R (e.g., see Hooey et al., 2000, 2002; Jones, 2008; Zeitlin, 2006). The elements of SA that are particularly relevant to this discussion are awareness of the position of potential conflict hazards and awareness of own aircraft position. These elements of SA have a static element (where is potential conflicting traffic now, where ownship is now) and a predictive element (where potential future conflicts are and where ownship will be when those conflicts might come into play). The working assumption that is relevant to TMA CD&R is that the better the displays that pilots have in terms of providing good situation awareness, the more likely they are to avoid blunders and conflict situations in the first place, and the more likely they are to react quickly and accurately if a conflict situation occurs. Below is a list of CVI equipage and concepts that should improve pilot situation awareness and thus increase safety by avoidance and resolution of conflict situations. A second list of CVI equipage and concepts aimed more generally at pilots' monitoring and managing tasks is also provided. These concepts should provide an indirect benefit to CD&R by helping pilots manage factors that affect workload, information load, decision making, and overall mission management.

CVI equipage and concepts directly relevant to CD&R:

- Synthetic Vision System (SVS) perspective airport views.
- SVS- EVS fusion.
- Airport moving map, surface guidance.
- CDTI (ADS-B, TIS-B, ASDE-X, etc. as sources).
- HUD and Near-to-Eye devices.
- Electronic Flight Bag (EFB) improvements.
- Multifunction Display (MFD) improvements.
- Low end carry-on devices.
- Integrated weather displays.
- Integrated, tailorable, electronic charts and maps.
- Graphical data link and flight planning interfaces.
- Display of data linked info (e.g., Flight Information Services- Broadcast (FIS-B) information).
- Terrain, obstacle, and airport database-driven alerts and advisories (e.g., Runway Awareness & Advisory System or RAAS).
- Increased integration of flight deck alerts.
- Taxi display—alerting integration.
- Error and discrepancy checkers.
- 3-dimensional (3-D) audio alerting, integrated multimodal alerting.

CVI equipage and concept improvements indirectly relevant to CD&R:

- "Non-normals" management aids.
- "Non-normals" communication aids.
- Pilot monitoring concepts and fatigue management aids.
- Adaptive user interfaces.
- Task and information management aids.
- Mission management aids.
- Automation management aids.

- Dynamic function allocation concepts.
- Strategic planning aids.
- Attention management aids.
- Energy management aids.
- Collaboration aids.
- Strategic safety aids.

### 4.3.3 Potential CVI-Crew Performance Issues

While CVI advances should help improve safety related to NextGen TMA operations, the operational changes envisioned, in conjunction with expanding pilot roles/responsibilities and CVI changes that generally make more information available to the flight crew, have the potential to negatively affect safety as well. For example, a more complex operational environment with more highly automated flight deck systems will likely exacerbate the age old issue of how to keep pilots involved and informed without overloading them with information and high workload. Further, more alerts, notifications and other types of information that compete for pilots' attention could create more distractions, interruptions, and disruptions in a very demanding multitasking environment, and it will be more and more difficult to maintain an overall quiet, dark cockpit philosophy that has been an important part of aircraft safety in the past.

Terminal area operations are typically high workload, and pilots often feel time pressure, especially during departure. Add quicker paced operations, closer spacing, RTAs, EVO, more communications, and flight crew stress/workload could increase significantly. Further, current terminal area pilot human factors issues such as aircraft energy awareness and management could be exacerbated as arrival and landing procedures become more complex and precise (e.g., Required Navigation Performance (RNP), RTAs, etc.). This volatile combination of increased operational, procedural, automation, and information complexity during operations that are more demanding with less margin for error, could easily offset all the benefits of additional technologies and equipage that are aimed at improving NextGen surveillance and CD&R. Figure 1 shows key potential pilot performance and human factors issues, and more detailed discussion of these issues is provided below.

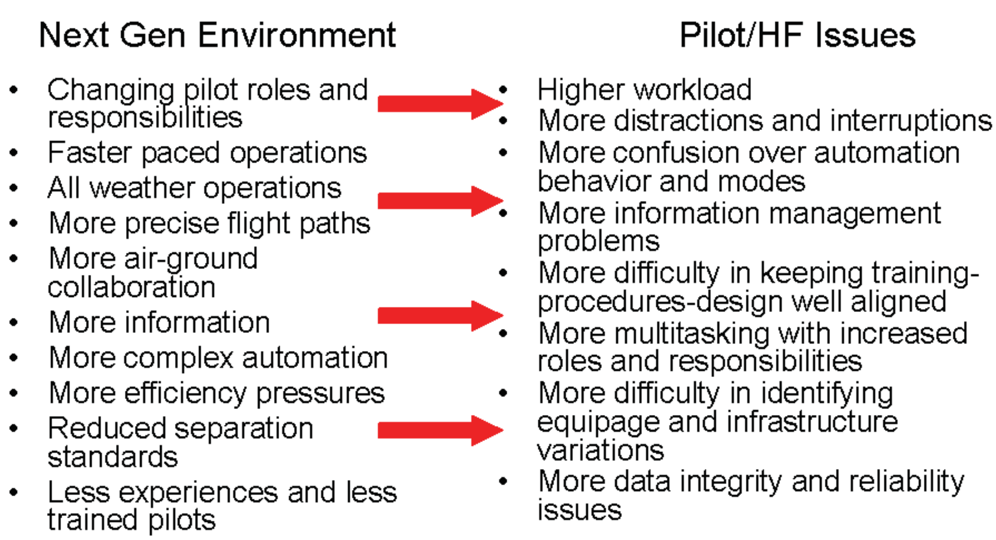


**Figure 1. Potential NextGen Pilot/Human Factors Issues**

1. *Higher Workload*. When workload is very high, subtle degradations in human performance occur. This can manifest as delays in response, errors, misjudgments, and poor decisions. Low visibility, more communications, more information, closer spacing, more precise navigation requirements, and faster paced operations all can lead to higher pilot workload. The frequency of "outliers" in terms of delayed or erroneous pilot responses to conflict alerts will be higher when workload is higher. Further research is needed to determine if the log normal curves for pilot response time used in the modeling effort accurately reflect the likelihood of response delays and errors under potentially higher workload conditions than are typical in today's environment.
2. *More distractions*. With more sources of information, more tasks, more communication, more alerts and notifications, pilots are likely to be more susceptible to distractions and interruptions in a NextGen environment. Distractions have the same basic effect on performance as very high workload – pilots' understanding of, and responses to, potential conflict situations are more likely to be delayed or erroneous if they are distracted by another task or other information that is not related to the situation at hand. The CVI challenge is to help manage the increased tasking, information, and alerts so that distractions are minimized (e.g., quiet dark cockpit philosophy), yet attention management assistance is provided to assure that pilots attend to the most important information.
3. *Increased automation confusion*. Both flight deck control automation and information automation will be more complex in order to meet the efficiency and safety requirements of the NextGen operational environment. Today's automation issues, such as lack of trust versus over-reliance on automation and processed information, pilot input and cross checking errors, misunderstanding of automation behavior and modes, especially in anomalous or unusual situations, are all likely to be exacerbated as future automation complexity and interconnectivity increase. The CVI challenge is to provide information and feedback to pilots that simplify the task of monitoring and managing the automation. The more layers and types of automation that are an integral part of surveillance and conflict avoidance, and the more information and information sources that must be processed and integrated by the pilot in order to understand and respond to possible conflict situations, the more likely errors and delays in response can occur. An important research issue to address is pilot response to conflict situations when surveillance automation and various information sources add an automation management/awareness task to the primary task of assessing the conflict situation.
4. *Increased information management demands*. Integration of information and information sources add "overhead" for pilots just as the need to understand complex automation behaviors and modes does. For surveillance and CD&R, this could become a critical issue if the sources and reliability of surveillance information vary by airport infrastructure and aircraft equipage, and if multiple sources of surveillance information are available simultaneously. Funk et al. (2008) identify issues such as, "procedures using different sources of traffic information (visual, ADS-B, TCAS-II, Air Traffic Control (ATC)) may lead to unsafe situations," and "lack of standardization of ADS-B cockpit equipment may lead to errors," as new opportunities for errors created by variations in CVI and surveillance advances such as ADS-B and CDTI.
5. *Difficulty in keeping training, procedures, and design aligned*. In addition to the concerns about the general trend toward less trained, less experienced pilots, the projected new equipage required to enable NextGen operations raises a "too much, too fast" concern about required changes in accompanying training and procedures. Pilots will use new equipment, requirements, procedures, and terminology that will require specific training. In order to make such wholesale changes in equipage and procedures successful from a pilot usability perspective, there is an added priority on CVI design to make the pilot tasks and interactions with the new systems as simple and intuitive as possible. Research is needed to assure that the aggregate of new systems, equipage, and procedures don't overwhelm pilots with system interaction and training requirements.
6. *More multitasking because of new pilot roles and responsibilities*. When considering new pilot roles and responsibilities, new operational requirements must be looked at, such as self separation, greater air-ground collaboration, time and trajectory based clearances and so on, but changes in pilot roles

and responsibilities as automation and information monitors and managers must be considered. This issue emerges from several of the other issues described above, such as greater information demands and higher workload, but needs to be addressed as a separate issue because envisioned changes to equipage and procedures can have such a profound effect on cumulative flight crew tasking in the more demanding phases of flight in a NextGen environment. The research issue that needs to be addressed here is how specific tasks such as CD&R are performed in a full mission environment, especially if the conflict is completely unexpected.

7. *Variation in operations, infrastructure and equipage*. Funk et al. (2008) summarized CVI and pilot performance issues related to these variations: "For the foreseeable future, aircraft equipped with ADS-B will share the airspace with aircraft that are not ADS-B equipped. Furthermore, ADS-B aircraft will need to operate in areas with and without radar coverage with varying degrees of ATC supervision. Thus, on a single flight an aircraft could fly from an area where ATC has primary responsibility for the separation of aircraft but all aircraft are visible to the flight crew on the ADS-B display, to airspace in which ADS-B aircraft continue to be displayed while non-ADS-B equipped aircraft disappear due to gaps in radar coverage. To ensure safe and efficient flight, different monitoring, communication, and avoidance procedures for different conditions must be developed and pilots must be trained in these procedures. Furthermore, displays will need to be built that will alert the pilot to the conditions in which they are operating. This will be especially important if NextGen plans, which call for the ability to dynamically shift airspace depending on weather and traffic demands, are implemented." In particular, Funk et al. point out potential CVI/pilot performance issues related to introduction of ADS-B and CDTI, and issues related to variations in that equipage:
   a. Pilots using CDTIs may be more likely to unsafely deviate from ATC clearances.
   b. Excessive use of CDTIs may reduce visual traffic scan skills.
   c. ADS-B equipment may increase workload and distractions.
   d. Pilots may become overconfident in and over-reliant on ADS-B.
   e. Pilots may not adequately understand ADS-B capabilities and limitations.
   f. CDTI placement may make displays difficult to read.
   g. CDTI display clutter may exacerbate conflicts.
8. *Data integrity and reliability issues*. Especially in EVO conditions where there may be no "raw data' by which to cross check or validate surveillance data from ground and airborne sensor sources, there will be greater need for data integrity and reliability. If there are differences in accuracy or integrity of data from different data sources, pilots will need some indication of what the performance levels of the systems are, or there will need to be some type of graceful degradation strategy such that data is not relied upon if it is deemed to be below some accuracy threshold. Further, if multiple sources of surveillance data are available, voting or fusing schemes will be required in order to present pilots with composite data to avoid confusion and the need for pilots to disambiguate disparate sources of data.

### 4.3.4 Potential impact of CVI and pilot performance on TMA CD&R safety levels

The assumption was made that CVI and pilot performance issues can have two main effects on TMA CD&R safety levels: (1) they can influence the probability of blunders and deviations, that is, the likelihood that a conflict situation arises in the first place; and (2) they can influence timely and accurate CD&R, that is, the likelihood that a conflict will be safely avoided once it occurs. While the probability of blunders and deviations was only assumed at a gross level in conjunction with the modeling analysis performed here, a short discussion of CVI and probability of blunders/deviations is provided below. Then, more importantly, a discussion of CVI and CD&R is re-visited in the conclusions, based on results of the modeling analysis.

1. Probability of blunders & deviations. NextGen CVI advances such as SVS, ADS-B, TIS-B, CDTI, taxi displays and guidance, data linked ground clearances, etc., are likely to significantly reduce the probability of blunders and conflict situations in terminal areas in a NextGen environment. Not only should pilots have better awareness of potential conflicts, they should also have more reliable and precise guidance in terms of assuring their own aircraft is where it should be. On the other hand, because of faster paced operations with smaller margins for error, and the multitude of issues that can lead to more pilot distractions, higher workload, more automation awareness issues, and so on, blunders could actually increase because of increased opportunities for human error. These conflicting scenarios, in terms of potential blunder and deviations probabilities, make this an important issue to address empirically as well as with parametric analyses.
2. Probability of safe CD&R. The modeling effort assumed a log normal response time curve for pilot reaction to conflict alerts (similar to that used in Kuchar and Hansman, 1996, but using response times judged to be more representative of airport operations). This is a simple assumption that could over- or under-estimate the expectancy of pilot response times due to not only individual differences, but to the benefits of CVI advances and the possibility of creating new pilot performance behaviors (as described above). In general, one might assume that conflicts which arise from "quantitative deviations," that is, tighter operations and smaller tolerances, where a potential conflict might occur, for example, because an aircraft is slightly early or late to an intersection, will result in generally quicker and less variable responses by pilots because they are more prepared and focused on the potential conflict situation. Conversely, conflicts which arise from "qualitative blunders," where an aircraft or another vehicle is not where it should be and is not expected by the other aircraft, will result in higher likelihood of pilot response "outliers" where abnormally slow or inappropriate responses may violate the assumptions of the pilot response time model used here.

Pilot responses in a variety of CD&R scenarios using full mission operational conditions should be assessed to validate the simple pilot response time models used here. Further, the current modeling effort did not account for erroneous responses – i.e., not performing the correct response and in some cases, doing the opposite of the appropriate response (e.g., turning left instead of right, stopping instead of accelerating). The potential for response errors such as these must be empirically evaluated as well.

## 4.4 Other NextGen Equipage Changes

While expected CVI and surveillance equipage changes were described in previous sections, there are many other equipage changes expected as well, primarily in communication, database, flight management, and navigation systems. These changes will enable precise trajectory and time-based operations, more precise aircraft position information relative to permanent obstacles and airport geometries, data linked communication of taxi clearances and more time-critical alerts and information from ground to aircraft, integration of flight planning, communication, and surveillance functions, and so on. The overall key equipage assumptions for generating the alternative NextGen environments for these analyses included: ADS-B Out, ADS-B In, cockpit moving map, TCAS, CDTI, basic and/or comprehensive alerting, database-driven airport surface alerts, data linked taxi routes, and uplinked alerting.

## 4.5 Ground Area Procedure Changes

The CD&R function anticipated for NextGen will exist with increasing deployment of technological advances in communication (air-ground data links, System Wide Information Management), navigation (area navigation (RNAV), required navigation performance (RNP)), and surveillance (ASDE-X, ADS-B, and LCGS). The use of Runway Status Lights (RWSL) and other lighting guidance will also increase. The use of CDTI to give flight crews immediate access to a representation of ownship position on an airport map and showing known traffic is expected to provide substantial benefits through reduction in errors and inefficiencies (such as hesitation). Some improvement in situation awareness is expected from the use of a moving map with ownship position.

NextGen is likely to bring many changes to ground procedures, as part of a continual drive to translate technology advancements into operational improvements. However, it is difficult to predict the final form of those procedures, as research continues to find matches between operational benefits and feasible equipage and support system improvements. For this study, it is assumed that NextGen procedural efficiency benefits will be based primarily on the following two mechanisms: improving average airport throughput by reducing inefficiencies caused by adverse conditions (congestion and/or bad weather), and enabling operations that are predictably more efficient by using time-based clearances (Surface Trajectory-Based Operations, or STBO) (JPDO, 2007). So far, the procedures envision conducting operations in bad weather that match the throughput known to be achievable in good weather. No advocacy for systematically increasing peak taxi speeds above those achieved in good traffic and weather conditions has been found. This is consistent with the general belief that congestion and maximum runway throughput are a greater detriment to airport efficiency than the peak taxi speed. Increased predictability of the taxi phase of flight is also desired; this goal will tend to discourage procedures based on increasing the maximum taxi speeds.

Therefore, initial assumptions were made that the limits on speed and separation of aircraft on runways and on the surface will be fundamentally unchanged, and that the effect of procedure changes will be primarily to:

- Enable speeds and spacing in poor weather that match those achieved under best-case conditions in good weather;
- Automate tasks (such as delivery of taxi route clearances) that presently make high demands on controllers, pilots, and the radio communication between them, reducing the need for consultation of maps and holding while awaiting instructions; and
- Selectively introduce new procedures (such as precise time-based taxi schedules aided by speed guidance in the cockpit) with the aim of improving overall efficiency, but only for the best-equipped aircraft.

The modeling assumed that a robust CD&R function must exist independently of any equipment designed to implement new procedures. The CD&R function will protect against any hazards that arise through failures (mechanical or human) in the new equipment and the way that it is used, in addition to current-day hazards.

In today's environment, aircraft and vehicle traffic in the movement area (taxiways and runways) is directed by one or more ground controllers working in the ATC tower, while departing and landing aircraft are directed by local controllers in the tower. Larger airports may have one or more ramp towers to direct traffic in non-movement areas, staffed by the airport authority or by individual airlines. The primary method of control and coordination is voice communication.

Surface traffic conflict avoidance begins with the taxi instructions (route and hold points) issued by the ground controller, complemented by visual separation, as possible and practical, by the flight crew as the taxi instructions are executed. Taxi instructions allow the pilot to proceed along the route to the next hold point identified in the clearance with spacing from preceding aircraft or vehicles at the pilot's discretion. (Controller clearance is now required for all runway crossings. Previously, instructions to taxi to the active runway were considered to imply clearance to cross any other runways en route). If visibility is extremely poor, controllers may change the instructions to provide more distance between aircraft, but separation responsibility remains with the pilot. Pilots may also request "progressive taxi" instructions (turn-by-turn instructions during taxi) as needed due to poor visibility or uncertainty in the airport layout. The availability of CDTI is not expected to alter the fundamental reliance on pilot responsibility for separation during taxi using "out-the-window" visual scanning. As ADS-B adoption becomes widespread under the Notice of Proposed Rule Making (NPRM) (FAA, 2007), it becomes more probable that all nearby aircraft (and vehicles at some airports) will appear on a CDTI; however, it cannot be guaranteed.

The chance of encountering a non-cooperative vehicle, a vehicle or aircraft with a failed transponder, or failure of the CDTI itself is nonzero, making it unlikely that procedures will be adopted that do not rely on visual scan for surface navigation. The doctrine for CDTI use is expected to be similar to TCAS, in that it increases situation awareness but should not be relied on for separation.

NextGen is also expected to move routine exchanges of information such as taxi instructions from voice channels to data link, with voice used for confirmation, runway clearances, and backup/contingency (i.e., voice by exception). Procedures and practices that insure consistency between the data link and voice communication will be required. The availability of a high-speed, low-latency data link is also essential to concepts proposed for the use of STBO. STBO implies that taxi instructions will include constraints on the times of arrival at waypoints along the surface route, and that these constraints are centrally coordinated by ATC to meet constraints on safety and efficiency. Some STBO variants extend as far as adding cockpit indications for the taxi speed required by the planned schedule. As this feature would require dedicated cockpit instrumentation, it was assumed that such procedures would not be widely used in the envisioned end-state.

## 4.6 Terminal Area Procedure Changes

### 4.6.1 RNAV and RNP Background

RNAV is the widely used avionics system that defines the three-dimensional reference path for the aircraft, and then provides automatic steering (guidance) signals or commands in order to follow that path. This reference path may come from the flight plan, be communicated to the aircraft from ATC / Air Navigation Service Provider (ANSP), or from direct pilot entry. RNAV provides a way to follow a more direct or optimal path without that path being anchored to ground-based navigation aids such as VHF Omni-directional Range (VOR). RNAV has been available for 40 years.

With the advent of precision navigation systems such as Inertial Navigation Systems and GPS, the concept of “required navigation performance” (RNP) has emerged. RNP is a measure of navigation accuracy that guarantees that the aircraft flying a prescribed route or path, such as from RNAV, maintains its desired position along that path within some specified set of parameters. It is a measure of how accurate the aircraft navigation and guidance systems are. RNP is currently used to specify how close to the route centerline the aircraft will be maintained during flight; that is, RNP specifies the maximum size of the flight path lateral or cross-track position error that would be expected during flight. For example, a navigation system with RNP of 1.0 nm will maintain the aircraft’s position along the reference path within 1.0 nm. As this capability evolves, both the vertical and in-trail / longitudinal accuracies will be added to the RNP specification.

The multiple uses of RNAV and RNP are very important to early realizations of several NextGen operational improvements. With very accurate lateral navigation along a more direct RNAV path, the following benefits can be obtained:

- Shorter, more direct paths can be defined that connect the beginning and ending points of a route segment. Shorter paths take less time and fuel saving operating cost and decreasing emissions.
- Smaller, more accurate RNP performance enables defining and using more paths within a given airspace volume. These paths can be more complex than if they are restricted to what an air traffic controller can readily command. This makes better use of the airspace, allows more flexible routing when airspace is restricted by storm cells, and, in general, enables greater overall capacity in congested terminal metroplex airspace.
- Aircraft with accurate RNP performance are more predictable in their flight progress making the job of the air traffic manager less demanding and more productive.

### 4.6.2 Precision Surveillance

The use of RNAV and RNP to enable flying more closely separated flight paths requires that the ground-based ANSP surveillance system ensure that the aircraft are successfully flying along these paths within the designated envelope expected for the flight. In other words, the applications of precision navigation and precision surveillance go hand in hand. If a flight path is defined with a small RNP value, and the aircraft / flight crew commits to fly such a path, then the surveillance system must have even greater accuracy than the RNP accuracy for monitoring the flight progress. It must assess the flight trajectory to assure that it is within its intended accuracy envelope, and if there is too large a deviation, for whatever reason, it must detect that unexpected error. Even more importantly, if the flight path error creates a risk of conflict with another aircraft or ground obstacle, the surveillance system must detect that conflict, and issue warning and conflict resolution instructions to the flight crews involved.

Thus, precision surveillance is another necessity and enabler for the NextGen applications of more precise, closely spaced aircraft operations within the congested terminal area. Existing Terminal Radar Control (TRACON) radars do not provide that accuracy. However, extending ASDE-X surveillance capability to implement a wide area multi-lateration (WAM) system does, in the near term. As more and more aircraft become ADS-B "Out" equipped, this equipage can provide the necessary surveillance accuracy with WAM serving as a suitable safety backup.

### 4.6.3 Parallel RNAV / RNP Approaches

#### 4.6.3.1 Application Description

A near-term example application of improved navigation and surveillance accuracy that exploits the capabilities of aircraft equipped with more accurate RNP capability is referred to here as "parallel RNAV / RNP approaches." In this application, those aircraft equipped with more accurate RNP capability get to fly more direct routes to the destination runway. To describe this, suppose that aircraft approaching a common runway can be divided into those with RNP of 1.0 nm and 0.3 nm; those with 0.3 nm RNP get approach route preference.

Figure 2 illustrates two parallel approach paths for aircraft entering the terminal airspace on the (long side) downwind legs. The inner path closer to the runway and more direct is the RNP 0.3 path. The outer path that is off-set further from the runway is for the RNP 1.0 aircraft. As the aircraft turn to base and then final, they are merged into a common path with appropriate in-trail spacing based on wake vortex and runway occupancy considerations.

This application can be extended to have the two paths end onto parallel final approach paths leading to parallel runways. That is, they do not necessarily merge into a single path. Another consideration is that a similar parallel path structure can be used to design the approach routes coming from the short side of the runway. The short and long side paths all merge onto the final approach extended runway centerline(s).

Figure 3 illustrates in more detail how the two parallel paths would be positioned. The centerline of the RNP 0.3 path is offset from the runway centerline the amount that allows aircraft on this path to turn to base and then final within the ride-comfortable turning envelope of the aircraft assuming it is 0.6 nm (4-sigma) to the right of centerline as it begins its base turn. The centerline of the RNP 1.0 path is offset from the RNP 0.3 path by 2.6 nm (to create a conservative 4-sigma cross-track separation between the parallel RNAV routes.)

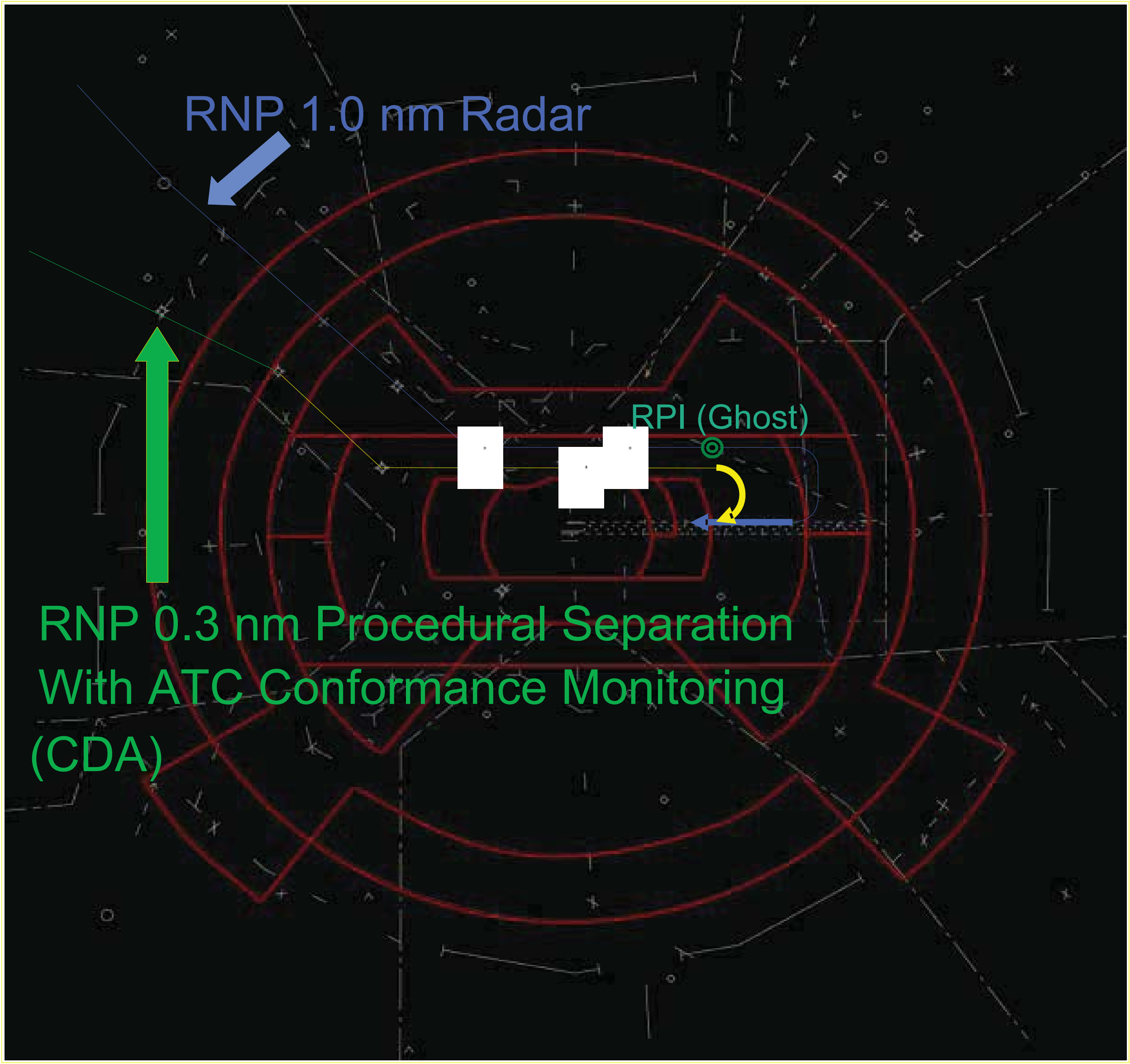


**Figure 2. Aircraft with Different RNP Capability Approach Runway on Different Paths**

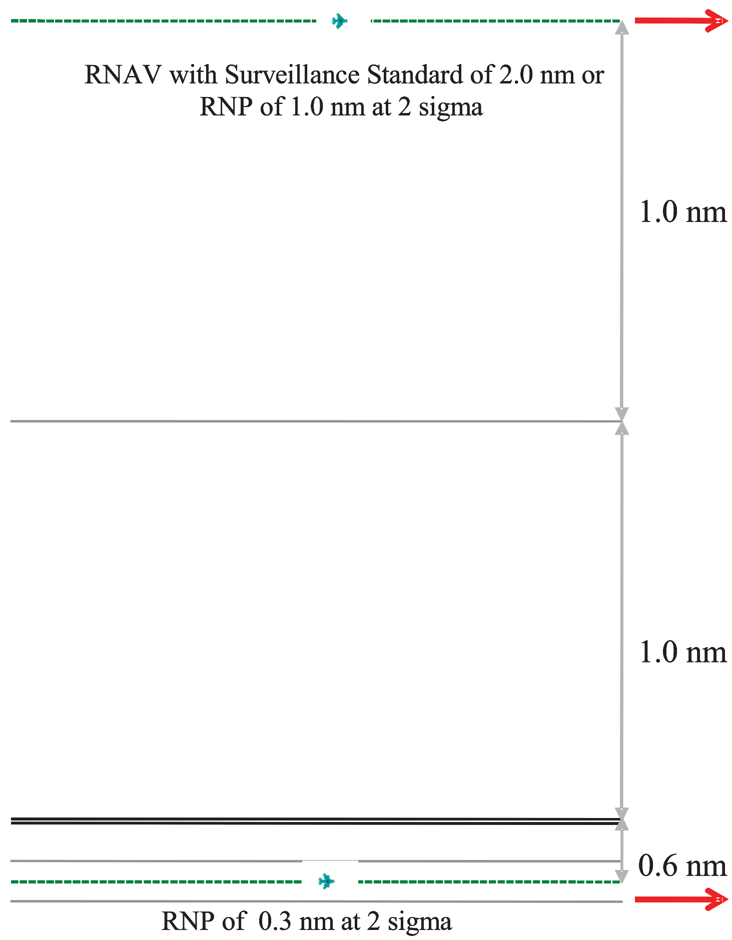


**Figure 3. Spacing Geometry Details for RNP-governed Parallel RNAV Approaches**

#### 4.6.3.2 Potential for Conflicts and Their Detection Requirements

There are two types of conflicts that must be addressed in considering the choice of spacing parameters for implementing the parallel RNAV/RNP approaches – cross-track error, and in trail spacing error. This conflict characterization is not unique to this particular example application, but is typical of all RNAV/RNP NextGen concepts.

#### Cross-track Error

In designing parallel or converging reference paths through a congested airspace, proper allowance must be made for the collective normal cross-track flight path errors due to imperfections or variations in navigation, reference RNAV path flight following ability (flight technical error), winds aloft, surveillance, and equipment failures. As shown in the earlier example, the parallel RNAV paths were placed the width of two RNP distances (2.0 nm plus 0.6 nm) apart. A parametric study is needed to determine what distances should be designed into the path separations in order that the cross-track conflicts due to highly unlikely errors would be kept to an acceptable level of safety.

In addition, the analysis must consider the possibility of a blunder caused by equipment failure, pilot negligence, or other cause. The blunder would be such that the aircraft on one of the adjacent paths would leave that path and fly into conflict with an aircraft on the other path. This analysis should determine that such a blunder would be detected by the surveillance system in time for the traffic manager to resolve the conflict.

### In-trail Spacing Error

Aircraft can be spaced closer together in trail by ANSP use of (a) a scheduling algorithm (such as used by the TMA function); (b) plan form display that shows projections of aircraft on routes that will merge; plus (c) desired inter-aircraft spacing indications that account for wake vortex, runway occupancy, and departure slot constraints. By spacing aircraft closer together in trail, this implies that tighter control must be maintained in keeping the aircraft within some error bound (deviation tolerance) of their desired relative positions in the schedule of incoming aircraft. These error bounds must be determined such that an envelope protection system can be designed to monitor the relative spacing, and so that procedures can be designed for the traffic manager to issue commands that will return an errant aircraft back into safe spacing tolerances or to leave the approach sequence and be placed at a later position for approach.

# 5. Analysis Methods

This section describes the analysis methods used to model NextGen CD&R.

The approach was to build models that credibly represent the most fundamental limitations on conflict resolution performance to first-order accuracy under the aforementioned assumptions. This approach was taken because of the infeasibility of forecasting the interactions on all conceivable NextGen developments, and because the study priority was to differentiate the performance associated with different cockpit and ground system technologies in an end-state representing full deployment.

The following steps were taken in developing the modeling approach and framework.

- Developed algorithms, software, and processes to model effects of interest.
- Determined form and parameters of models for:
  - Surveillance accuracy,
  - CD&R decision variable accuracy,
  - CD&R decision threshold determination, and
  - Probability of each type of interaction (encounter) between each assumed category of aircraft.
- Developed techniques for estimating model parameters via analysis or simulation.
- Used plausible rationale for assumed environment and systems.
- Avoided disproportionate effort on second-order effects.
- Concentrated on analytical models as basis for future requirements.
- Built analytical foundation rather than system architecture.
- Assumed reasonable requirement allocation (i.e., no unrealistic mandates).
- Assumed solutions to peripheral issues could be developed.
- Built framework to connect the results of separate models into general conclusions.

## 5.1 Modeling Baseline and Alternative NextGen Environments

Four NextGen environments were considered, representing a baseline end-state (NextGen 1) and three variants. Aircraft were divided into 3 major classes, as will be discussed in Section 5.1.3. After extensive discussions of the expected equipage levels, a consensus on representative and plausible equipage combinations was reached. The minimum ADS-B equipage was assumed to be ADS-B Out, in keeping with the current ADS-B NPRM. Table 2 summarizes the alternative NextGen environments for purposes of this study.

**Table 2. Summary of Alternative NextGen Environments**

| Label | Transport—New | Transport—Retrofit | Non-Transport |
|---|---|---|---|
| NextGen 1 (Baseline) | ADS-B Out<br>Cockpit moving map with ownship position<br>TCAS or successor Airborne Collision Avoidance System (ACAS) | ADS-B Out<br>Cockpit moving map with ownship position<br>TCAS or successor ACAS | ADS-B Out<br>Cockpit moving map with ownship position |
| NextGen 2 | ADS-B Out, ADS-B In<br>CDTI with ownship, traffic, alert presentation<br>On-board alerting for basic runway hazards<br>TCAS or successor ACAS | ADS-B Out<br>Cockpit moving map with ownship position<br>TCAS or successor ACAS<br>On-board indication/alerting for non-traffic hazards | ADS-B Out<br>Cockpit moving map with ownship position |
| NextGen 3 | ADS-B Out, ADS-B In<br>CDTI with ownship, traffic, alert presentation<br>Data-linked taxi routes<br>On-board alerting for comprehensive hazards (taxiway, low-altitude, expanded runway)<br>TCAS or successor ACAS | ADS-B Out, ADS-B In<br>CDTI with ownship, traffic, alert presentation<br>Data-linked taxi routes<br>On-board alerting for basic runway hazards<br>TCAS or successor ACAS | ADS-B Out, ADS-B In<br>CDTI with ownship, traffic<br>On-board alerting for basic runway hazards |
| NextGen 4 | ADS-B Out, ADS-B In<br>CDTI with ownship, traffic, alert presentation<br>Uplinked alerting for comprehensive hazards (taxiway, low-altitude, expanded runway)<br>TCAS or successor ACAS | ADS-B Out, ADS-B In<br>CDTI with ownship, traffic, alert presentation<br>Uplinked alerting for comprehensive hazards (taxiway, low-altitude, expanded runway)<br>TCAS or successor ACAS | ADS-B Out, ADS-B In<br>CDTI with ownship, traffic, alert presentation<br>Uplinked alerting for comprehensive hazards (taxiway, low-altitude, expanded runway) |

#### 5.1.1 Conflict Scenarios

The analysis employed five conflict scenarios. The scenarios were chosen to include instances of taxiway, runway, and low-altitude conflicts and to show a variety of conflict geometries. The chosen scenarios were:

- Arrival and landing with taxiing aircraft crossing runway.
- Two arrivals to intersecting runways.
- Two aircraft taxiing along same path with following aircraft overtaking.
- An arriver approaching the runway while the previous landing aircraft is still on the runway.
- RNAV / RNP approach to same runway using parallel paths.

The geometry and parameters of the scenarios analyzed are described in subsequent sections. Other scenarios considered included: two aircraft taxiing toward a common intersection; an aircraft departing as another arrives to a closely-spaced parallel runway; and simultaneous approaches to parallel runways.

For each scenario, there are many possible formulations of tests to discriminate between safe and unsafe encounters. For this study, an attempt was made to identify the most critical decision variable, based on sensitivity to the joint surveillance quality of the aircraft involved. This approach recognized that “tight”

operations, such as those associated with maximum airport throughput, generally put maximum stress on CD&R discrimination.

### 5.1.2 Model for Equipage Adoption

The models were intended to mimic end-states in which the transition to one of the four alternative NextGen environments has occurred. The goal was to provide clear differentiation of the potential safety improvement realized under each alternative, in order to guide further research and possibly policy decisions. Early in the study, the approach of predicting risk levels throughout a “build-out” period concluding in an end-state of full NextGen equipage (according to one of the four NextGen environments described in Table 2) was considered. However, this approach was rejected for two main reasons.

First, the effort to evaluate effects over a period of incremental adoption was far more complicated than modeling the end-state and the effort was judged to be impractical. The problem of predicting the incremental safety benefits of partial equipage during the build-out period merits a separate study. In addition to postulating an adoption timeline for each equipage improvement considered, many more combinations of equipage and ground systems would need to be evaluated in the performance models. For example, it is likely that the mix of transport aircraft will include many combinations of Mode S position reporting and associated situation awareness and conflict detection technologies until full adoption and standardization are completed. Also, the timeline for training flight crews with the evolving technologies, and the rate of introduction of new procedures using the technologies, would also need to be modeled to produce meaningful results.

Second, introducing a gradual adoption rate would tend to dilute the improvements associated with each technology in the end-state, making the study less useful in differentiating the effect of alternative NextGen equipage levels.

Therefore, it was assumed that each NextGen alternative represented a steady state with a defined level of equipage (equipment installation) for each defined aircraft class. The set of classes used are described in the next section.

### 5.1.3 Aircraft Classes

Although the study considered only possible NextGen “end-states,” the population of aircraft in each assumed end-state was non-uniform, guaranteeing that encounters between aircraft with different equipage were considered. The approach was to limit the model to three classes -- “New Transport,” “Retrofit Transport,” and “Non-Transport.” Within these classes, equipage characteristics were chosen to match the lowest common denominator, representing the anticipated minimum equipment level for each class. Therefore, although older transports or high-end general aviation (GA) (i.e., Non-Transport) aircraft may voluntarily invest in high-performance GPS, ADS-B In, and a comprehensive on-board CD&R capability, these features are not expected to be required for all aircraft in that class, and so no credit for the advanced capabilities beyond the minimum equipment level will be given. It is assumed, however, that advanced equipment is designed for compatibility with other systems so that the advanced capabilities are not detrimental to safety.

### 5.1.4 Assets Used in Conflict Detection and Resolution

The ability to perform CD&R in a given encounter between two aircraft depends on the interaction of multiple ground and aircraft assets, including communication, surveillance, conflict detection, and conflict alert presentation. The services available are assumed to include all ground infrastructures required for effective ADS-B, such as ADS-R, to communicate information between aircraft on different data links (Mode S and Universal Access Transceiver (UAT)). For surveillance, an end-state with universal ADS-B Out (or equivalent) has been assumed; therefore, variations between airports, specifically whether ASDE-X surveillance was provided, were not modeled. Obviously, primary surveillance is necessary for safe management of a mixture of cooperative and non-cooperative mobile

objects; therefore, the model did not address the risks of using vehicles without transponders or equivalent surveillance.

The assumed capabilities for conflict detection and subsequent alerting vary according to the perceived difficulty of development and installation or retrofit. Generally, a higher level of alerting capability was assumed for new transport aircraft, and a lower level for “non-transport.” This ignores the likelihood that “high-end GA” (such as private jets or air taxi) may well have surveillance and conflict detection equipment; however, no credit for the possibly improved CD&R performance of this aircraft class was taken.

The costs of providing a certified CD&R capability rise significantly if it is made comprehensive. Recognizing that there is disagreement about whether CD&R is effective in some environments, such as airport taxiways, the various NextGen alternatives assumed different levels of alert generation and presentation capability. In contrast, the most comprehensive ground-based alerting capability was assumed to be available to all aircraft. This in turn was based on the assumptions that CDTI will be available for all aircraft classes and NextGen end-state, that necessary alerts can be effectively presented on the CDTI with negligible retrofit costs, and that the full-featured ground-based alerting will be provided at every airport, because the development effort can be performed once for the entire NAS.

An infrastructure to rapidly distribute any ground-generated alerts via data link was also assumed to be available, as a cockpit data link is desired for many other purposes (such as communication of TBO clearances.) The bandwidth required to transmit infrequent time-critical alert messages should be small compared to the bandwidth needed for routine exchange of taxi instructions and schedules.

### 5.1.5 Encounter Rates between Aircraft Classes

There are many difficulties in quantifying the rate at which aircraft in specified classes will operate in close enough proximity to be considered candidates for conflict detection alerts. The study used a simple model for NAS -wide effects by assuming that each of the aircraft classes modeled represented a fraction of all NAS operations, and that encounters between each class of aircraft occurred in proportion to their representation in the population of NAS operations. This model ignored the variations in aircraft class representation correlated to airports, specific runways, and daily, weekly, or seasonal cycles. (As an example, the proportion of GA aircraft operations at Milwaukee (MKE) on a fair weekend day will be relatively high and the proportion of GA aircraft at New York John F. Kennedy (JFK) on a rainy weekday morning will be relatively low.) Aside from the complexity of gathering data to analyze these correlations, there is every reason to believe that new NextGen procedures may create new correlation patterns, for example, by reserving a runway or an approach corridor for a better-equipped class of aircraft. These interactions should be considered if the approach used in this study is extended to a more detailed analysis of safety capabilities. More specific definitions of assumed procedures, particularly those linked to equipage, and the assumed changes in the population of aircraft operations by class or type, would be needed to perform such an analysis.

### 5.1.6 Selected Safety Metrics

The majority of the analysis effort was focused on estimating the ability of an assumed CD&R capability to prevent a collision, conditioned on the assumption that a conflict occurs in a particular assumed NextGen environment. The metric developed for this ability is referred to as the Conditional Collision Prevention Capability (CCPC).

The CCPC makes use of first-order models for pilot response time and assumed kinematic state accuracy variability, based on realistic models of surveillance and estimation errors. The CCPC also differentiates between qualitative (“blunder”) and quantitative (“deviation”) error mechanisms, and accounts for variations in conflict detectability between multiple potential alert sources (on-board either aircraft involved, or uplinked from a ground CD&R system.)

The CCPC is emphasized because it is easier to estimate the effectiveness of a safety capability than to predict how often it will be required. The model elements involved in measuring CCPC are relatively well-defined and clearly show the effects of equipage capabilities. In contrast, due to the difficulty of predicting error rates in future environments for which the procedures, workload, and mix of aircraft types are unknown, there is much more uncertainty about the rate at which conflicts could be expected to develop in the assumed NextGen environments than there is in the capabilities of the assumed CD&R systems.

However, a model based on simple assumptions about these error rates has been developed so that the relationship between individual conflict detection capabilities and overall system safety levels can be explored. Further research is strongly recommended to validate the assumptions used in these scenarios. For example, the rate at which blunders are avoided due to improvements in general situation awareness strongly affects the incremental benefits to be derived from providing CD&R coupled with alerts.

For each NAS aircraft class, the assumed level of equipage and ground support systems (as a function of NextGen scenario) was associated with three contributing factors:

1. A driving rate of **lapses** that could lead to conflicts (typically pilot deviations or operational errors).
2. A fraction ("yield") of lapses that result in **potential conflicts** eligible for alerts (complemented by the fraction of lapses that are resolved prior to alert eligibility).
3. A fraction of potential conflicts for which alerts are generated in time for **successful conflict resolution** by the specified alert source (implying that no party involved acted to prevent the lapse from becoming a potential conflict).

In other words, for each encounter type and each assumed equipage/ground system combination, the model assumed that there is a fixed probability of noticing a problem and resolving it before it becomes detectable as a potential conflict. The assumed mechanism is that there is an underlying rate of potential errors due to lapses; of course, the lapse rate itself could be affected by changes in pilot or controller workload and environment, as described in Section 4.3. Assuming that lapses remain undetected due to deficiencies in information availability or presentation, improvements in situation awareness should reduce the yield of potential conflicts from lapses. Therefore, the assumed introduction of CDTI into all aircraft in each of the assumed NextGen end-states will reduce the rate of potential conflicts, even before considering the benefits of CD&R.

The model implicitly assumed that the performance of each party to a potential conflict (Aircraft A, Aircraft B, or controller) in either noticing the conflict or reacting to an alert is independent. Therefore, there are multiple parties who can act to resolve the situation, which increases the assumed system effectiveness. The possibility of interference between resolution actions (for example, A's response tends to diminish the benefit of B's action) was not considered. This is an area for which further research is recommended to determine whether there are "common mode" effects reducing the assumed benefit of independent conflict prevent actions. For example, if both A and B rely on a single source of information for a critical parameter such as B's position, and that source is incorrect, the probability of a correct response between the two is correlated, violating the assumption of independent performance.

## 5.2 Analysis Framework

The analysis framework was based on the use of many first-order models to capture all the major dependencies in system performance. The goal was not to develop an alerting system as such, but to describe the expected performance limits of possible systems parametrically in terms of surveillance and equipage provided. In order to get comparable performance limits across scenarios and with different assumed NextGen environments, a consistent approach to each environment was needed.

Figure 4 shows the elements of the analysis framework used to insure a consistent modeling approach.

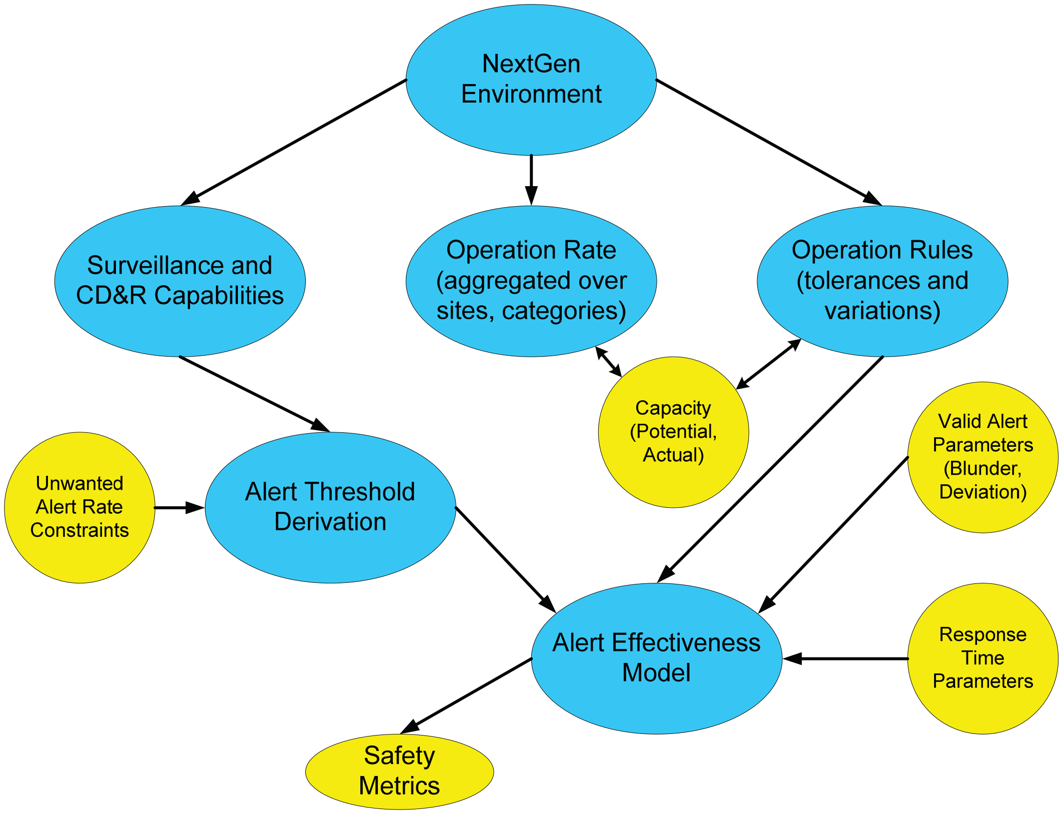


**Figure 4. Analysis Framework for Alerting Capability Model**

## 5.3 Trades and Decisions for Modeling Analysis

### 5.3.1 Response Time Model

For purposes of modeling pilot response times (RT) in these analyses, a set of simple log normal curves of pilot response times to alerts was used. The basic log normal RT curve was proposed by Kuchar and Hansman (1996), and using the RT variations proposed by Stanton (2006) based on the alarm initiated activity (AIA) model (see Table 3), plausible variations of the basic log normal curve (see Figure 5) were created based on differences in predicted pilot workload and degree of readiness for different conflict scenarios (see Table 4). It should be noted that while very simple pilot response time assumptions were used here, much more sophisticated human performance models (e.g., Foyle et al., 2005; Glenn et al., 2005; Kuchar et al., 2000; Lee et al., 2004; Pritchett et al., 2002; Reising et al., 2004; Tyler et al., 1998 ) could be applied for more rigorous analyses in the future.

**Table 3. Distribution of RT's per the Alarm Initiated Activity Model (Stanton, 2006)**

| AIA | Minimum RT (sec) | Maximum RT (sec) |
|---|---|---|
| Observation | 1 | 2 |
| Acceptance | 1 | 8 |
| Analysis | 2 | 6 |
| Investigation | 6 | 40 |
| Monitoring | Variable | Variable |
| Correction | 7 | 80 |
| Total | 17 | 136 |

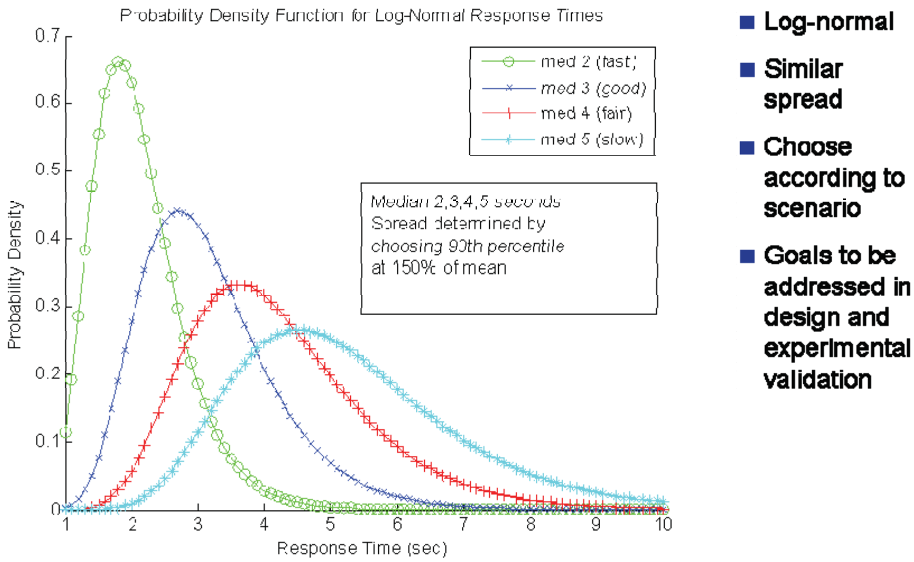


**Figure 5. Notional Response Time Distributions**

**Table 4. Assignment of Response Time Curves to Conflict Scenario Types**

| Activity / Source of Conflict | Crew Readiness for Potential Conflict | Competing Workload | Applicable Response Time Model | Response Times (Median, 90%) in seconds |
|---|---|---|---|---|
| Takeoff own runway | Medium | High | Good | 3.0, 4.5 |
| Landing own runway | High | High | Good | 3.0, 4.5 |
| Taxi on runway (before entry) | High | Low | Fast | 2.0, 3.0 |
| Taxi on runway (along, crossing) | Medium | Low | Good | 3.0, 4.5 |
| Taxi intersection | Low | Medium | Fair | 4.0, 6.0 |
| Taxi following | Medium | Low | Good | 3.0, 4.5 |
| Takeoff/Landing parallel runways | Medium | High | Fair | 4.0, 6.0 |
| Takeoff/Landing other runways | Low | High | Slow | 5.0, 7.5 |
| Terminal Area – prior to base leg | Low | High | Slow | 5.0, 7.5 |
| Notes: Best practices in CVI design and training will be required to achieve desired responsiveness. Indications that promote situational awareness and aid conflict identification are essential. | | | | |

### 5.3.2 Surveillance Accuracy Models

Information on the capabilities and limitations of GPS receivers, assumed to be the primary basis for ADS-B outputs, was described in Section 4.2. A reduced set of phenomena were included in the models used to generate analysis results.

Position measurement errors were assumed to be zero-mean Gaussian noise; this simplification grouped both lightly- and heavily-damped Gauss-Markov errors as white noise. This model also ignored the effects of systematic bias; based on Table 1, these biases are unlikely to be large enough to affect alert decisions. The principal model parameters were the standard deviation of position measurement error and the standard deviation of velocity error. These values were consistent with the ranges shown in Table 1; however, the range used depended on the assumed equipage model, and statistics for a given aircraft varied between random trials in Monte Carlo simulations.

The state information (position, velocity, and acceleration) was initially modeled as the products of a process to smooth recent position measurements within a fixed time window. However, GPS receivers are also capable of measuring velocity without using multiple position measurements, generally producing more accurate velocity measurements as described in Section 4.2. The assumed errors in velocity derived in this way can be much smaller than the errors achievable through short-term position smoothing of an aircraft moving on the surface. Furthermore, the errors in GPS-derived velocity may be largely decorrelated from errors in GPS-derived position, to the extent that the velocity errors are due to noise in the measured frequency shift of satellite signals rather than to noise in the measured time delay difference. The degree of decorrelation depends on the details of the GPS state estimation process. For this study, it was assumed that GPS-derived velocity errors were independent of position errors. For simplicity, the models used for simulating surveillance accuracy implement only Gaussian measurement errors, representing only a subset of the phenomena affecting accuracy described in Section 4.2.

Compared to the simplified accuracy model, the root mean square (RMS) estimated state error of a more advanced process such as an extended Kalman filter (EKF) could be smaller. However, it is not clear that the EKF would be optimum, since the quality of alert decisions may be affected more by the rate of unacceptably large errors from the “tails” of the distribution rather than the standard deviation of error.

### 5.3.3 Alerting Process Model

Due to the sensitivity of alerting behavior to the details of the surveillance source (particularly the “tails” of error distributions), practical alerting algorithms tend to be designed around a specific surveillance source and validated against a large volume of sample data. For the current study, it was judged impractical to develop a complete, robust alerting algorithm. Instead, a simplified model of the alerting process was used, with features sufficient to show the effect of surveillance accuracy on alerting performance.

In keeping with this approach, it was assumed that any practical alerting system would be subject to the constraints listed below. This assessment is based on experience with conflict alert algorithm design for ASDE-X and various international A-SMGCS systems.

#### Alerting Assumptions

- Alert decisions require the ability to discriminate between permissible and potentially hazardous interactions.
- Alert decision thresholds set a ceiling on system effectiveness in two major ways:
  - Limited situation coverage (alerting may be inhibited by design in situations that otherwise would generate excessive alerts).
  - Limited warning time (if alerts are delayed until confidence is high enough to meet nuisance alert requirements, the probability of a safe outcome may be reduced).

- Systems must limit total number of all unwanted (false and nuisance) alerts to an acceptable rate for certification and operational acceptance by users:
  - A nominal limit on the rate of unwanted alerts of $10^{-5}$ per operation[2] was assumed (higher rates may be tolerated in some contexts, such as taxi).
  - If standards permit higher rates for less-severe alerts, the concept of "downgrading" an alert (to caution or advisory) in cases where geometry or surveillance make the nominal rate unachievable[3] could be beneficial (for this study, only a single level of alert severity was considered).
- The total unwanted alert rate should be allocated between all contributing causes to derive realistic thresholds. However, in order to limit the number of Monte Carlo trials used in this initial study, each alert type was tested against a single relatively strict criterion limit requiring a nuisance alert rate due to predictable surveillance noise less than $10^{-5}$ per modeled encounter. Additional work would be required to estimate the encounter rate per operation and the combined rate from all sources.

## Alert Categorization

- Unwanted alerts are divided into the following categories for this analysis:
  - Alert caused by equipment failures.[4]
  - "Nuisance alert", here defined as non-beneficial alerts generated during normal operations with alert input sources operating within normal bounds, further divided into two subcategories:
    - Discrete errors caused by qualitative errors in assessment of situation:
      - False targets or false reports (excessive position error).
      - Incorrect assessment of current or intended movement state.
      - Wrong predicted arrival runway.
    - Parameter errors caused by quantitative errors in alert discriminants:
      - Predicted time to enter or clear runway or intersection.
      - Predicted position at time of another significant event.
- Acceptable alerts:

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[2] The rate of $10^{-5}$ per operation is comparable to the acceptance criteria for unwanted alerts during runway operations for ASDE-X safety logic, and is also within an order of magnitude of TCAS Resolution Advisory nuisance alert requirements. This value was proposed to RTCA SC-186 as a basis for setting requirements for flight deck alerts; however, the draft standard has relaxed this requirement to $10^{-3}$ per operation. These values are applied during flight situations when the consequence of an unwanted alert are relatively high, possibly leading to an unnecessary missed approach or rejected takeoff; therefore, it seems plausible that higher levels of nuisance alerts could be tolerated in taxi situations, where the disruption caused by an unnecessary stop is less.

[3] This approach assumes that the goal is to provide as great a safety benefit as possible for a surveillance source of fixed quality. It also assumes that lower-severity alerts (that do not demand immediate operator response) may be tolerable at higher rates than warning alerts, and could still provide a safety benefit, for example through improved situation awareness. This approach is not completely satisfactory, but may be preferable to the alternative of disabling alerting output in situations where the potential danger cannot be confirmed through available surveillance at an acceptable unwanted alert rate.

[4] The term "false alert" is limited to alerts caused by equipment failures, i.e. operation outside design specifications, in RTCA SC-186 WG-1 documents.

- Tolerable (justified by apparent conflict or procedural irregularity).
- Necessary (contributes directly to prevention or resolution of real conflict).

- The tolerable unwanted alert rate could depend on the type of alert or indication. (Notional values proposed to the RTCA SC-186 WG-1 effort to define requirements for Surface Indications and Alerts (SURF IA) for flight deck use were rates of $10^{-5}$, $10^{-4}$, $10^{-3}$, and $10^{-2}$ per operation for Warning, Caution, Traffic Indication, and Runway Status Indication, respectively).

In order to limit the scope of the current analysis, only single-level (warning) alerting and the resulting safety benefits were modeled. It was anticipated that for some scenarios (with worse sensors and more stressing timeline), the desired warning time couldn't be met at a specified unwanted alert rate. By measuring the overall CD&R capability with "coverage" metric showing the probability of successfully preventing collision over an ensemble of conflict situations, the limitations of each assumed NextGen capability will be shown in a consistent way. However, the analysis performed only addressed the probability of unwanted alerts due to parametric error in situation discriminants. It would be necessary to limit discrete errors (incorrect identification of the situation) to a comparable or lower level to achieve the desired unwanted alert rate.

# 6. Model Results

## 6.1 Common Simulation Elements

### 6.1.1 Trajectory Models

Aircraft were modeled along their primary axis of horizontal motion. Lateral deviations were assumed to be small and not relevant to the alerting process. The vertical profile (for landing aircraft, for example) was not modeled, as the modeled alerting process does not make use of it. It should be noted that to the extent that the measured height of the aircraft could be used to predict parameters such as touchdown position, it is possible that the alerting process could be improved relative to the results presented here.

Motion along the primary axis was modeled as a series of constant-acceleration segments. For example, a landing aircraft approaching at constant velocity, after touchdown, brakes with constant deceleration, and upon reaching a final rollout speed, taxis with constant velocity (this model is discussed in greater detail in Section 6.2.2). The constant-acceleration model, though not realistic, was sufficient to illustrate the features of alerting systems and the dependence on various parameters.

### 6.1.2 Aircraft Extent

The physical extent of each aircraft was modeled with three parameters: length, wingspan, and the position of the wings along the length of the aircraft. The aircraft was modeled as two line segments – one representing the fuselage and a perpendicular one representing the wings, as shown in Figure 6. Aircraft traveling on the same path collided if their fuselage line segments overlapped. When two aircraft's paths intersected, an intersection region on each path was defined by the area swept out by one aircraft's wing as it crossed the other's path. For the time interval that any part of the aircraft (nose, tail, and/or wingtip) was in the intersection region, that aircraft was considered to be in the intersection. A collision was assumed to occur if both aircraft occupied the intersection at the same time, as illustrated in Figure 7.

Encounters were simulated with a variety of real aircraft parameters. In each encounter, the type for each aircraft was randomly chosen (based on the assumed proportion of each type) and the appropriate size parameters were assigned.

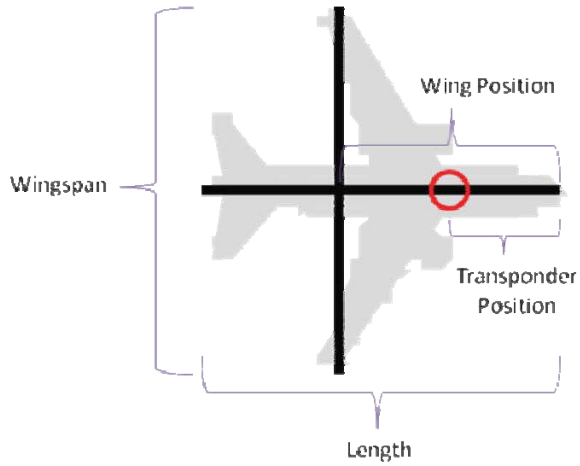



**Figure 6. Model for Aircraft Extent**

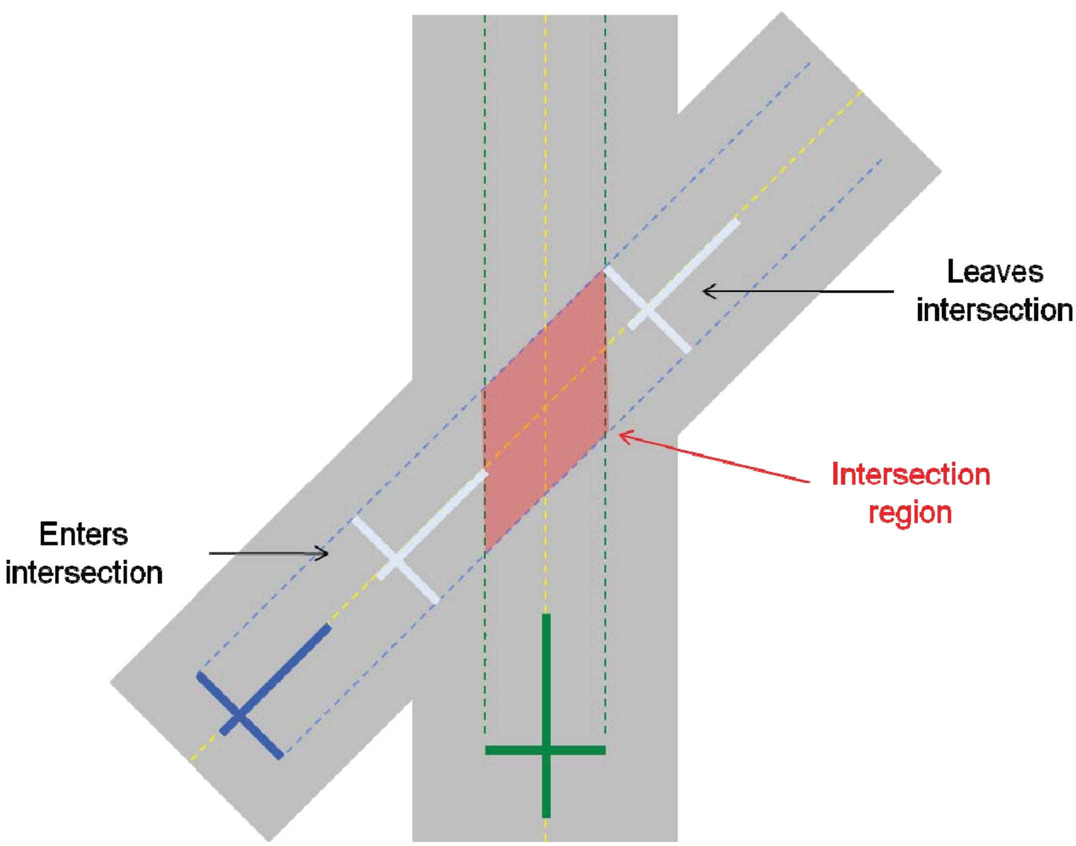



**Figure 7. Definition of Collision Potential**

Additionally, the position of the transponder was defined along the aircraft fuselage. Measurements were modeled as unbiased estimates of the transponder position, rather than of the aircraft centroid; it was assumed that all alerting systems modeled the asymmetric displacement of nose and tail positions relative to the transponder. From the measured transponder position and the aircraft size, the measured nose, tail, and/or wingtip positions were calculated. From these, the separation between, for example, a lead aircraft's tail and a following aircraft's nose may be calculated.

It was assumed that, in the NextGen environment, aircraft will transmit accurate information about their physical size. Therefore, the alerting system used the true size parameters to evaluate the separation between aircraft. Uncertainty in the exact position of the transponder on each aircraft was accounted for by adding an additional 5 m to the modeled uncertainty in all position measurements.

### 6.1.3 Measurements

It was assumed that position and velocity measurements will be derived primarily from GPS. The data was generated once per second, with each aircraft performing measurements at the same time.

Position measurements were assumed to have a 5-meter, Gaussian-distributed error. Each measurement was generated by adding to the true position an error randomly drawn from a Gaussian distribution with 5 m standard deviation. As such, 95% of measurements were within 10 m of the true position. Variations in the standard deviation parameter were also explored, but unless otherwise noted a value of 5 m was used.

It was assumed that a velocity measurement was also available from the GPS receiver, with negligible correlation between position and velocity errors, as discussed in Section 5.3.2 (both position and velocity are still derived from the same surveillance subsystem). As this represents a significant accuracy improvement over the velocity than can be derived from smoothing position, the effect of removing the assumed independent velocity source was examined in sensitivity analyses discussed later in Section 6.2.7.3. The velocity measurement was modeled by adding a Gaussian error to the true velocity. The standard deviation is 0.03 m/s for Transport aircraft (both New and Retrofit) and 0.10 m/s for Non-Transport.

Any alerting system resides either on-board an aircraft, or on the ground. A system must receive reports via ADS-B for all aircraft other than ownship (or for all aircraft in the case of a ground-based system). On-board systems use the source measurement model for ownship, and the reported measurement model for all other aircraft. The ground-based system uses the reported measurement model for all aircraft.

The ADS-B reporting process was modeled as follows. A random time delay uniformly distributed between 0 and 1 second was added between the time of the measurement and the reporting of that measurement to others. The system receiving the measurement knows the measurement time, but cannot act on it until the later time when the report was issued. Furthermore, the Mode S data link assumed for baseline ADS-B data provides only coarsely quantized reporting of measurement uncertainties. The quantization was modeled for reported measurements by using only values of 0.3 m, 1 m, 3 m, 10 m, 30 m, *etc*. for position uncertainty or 0.01 m/s, 0.03 m/s, 0.1 m/s, 0.3 m/s, 1 m/s, *etc*. for velocity uncertainty to be reported. The true uncertainty was rounded up to the next highest allowable value, and this higher value was reported. All other aircraft used the higher uncertainty.

### 6.1.4 Position and Velocity Estimation

The current state estimate was computed using algorithms based on fitting curves to measurements received over a fixed duration. A time window of 10 seconds was chosen based on experience with aircraft trajectory prediction in the airport environment. The window estimation method was used because the implementation is simple, the error characteristics are well-defined, and because it tends to be robust when the properties of the input measurement error distribution are uncertain, particularly the length of

error distribution "tails" and the correlation of errors in time. A fit to all measurements within the assumed time window was used to generate the estimate of the current position and velocity used in the simulated conflict detection algorithm.

When it was assumed that an aircraft was traveling at constant velocity, a linear fit to position measurements was performed as a function of time, and from this fit, the current position and its uncertainty were computed. The fitted position has a smaller uncertainty than the individual measurements. The last measured velocity and its uncertainty was used as the estimated current velocity. When an aircraft had non-zero acceleration, position and its uncertainty were estimated with a quadratic fit. Current velocity and its uncertainty were estimated with a linear fit to the measured velocity as a function of time. As discussed in Section 5.3.2, the simple model was considered to be sufficiently representative of the expected state estimation performance; an alternate estimation technique such as an Extended Kalman Filter would have required greater development effort and might well prove less robust in operational conditions.

### 6.1.5 Projected Quantities

The alerting algorithms required projections, such as the time margin between when two aircraft would occupy an intersection, or the smallest separation two aircraft would have in the future. These projected quantities were compared to thresholds to determine whether an alert should be issued. The projection computation was assumed to be applied in the same way regardless of the measurement model (source or reported measurements), as the projection used the provided uncertainty parameters.

Calculation of projected quantities always included calculation of the uncertainties on those projections. The uncertainties came from two types of sources: measurement and assumed future behavior. For example, to predict when a taxiing aircraft will clear a hold line the uncertainty on the current estimated position and velocity needed to be accounted for, as well as the possible magnitude of future speed fluctuations. Often the uncertainties due to assumed future behavior are larger than those due to measurement; in these cases, improved information about pilot intent would be more valuable than improved measurement of the current state.

## 6.2 Scenario 1: Taxi Crossing Arrival Runway

### 6.2.1 Overview

Figure 8 shows a diagram of the scenario. An aircraft taxied across an active runway at an intersection a variable distance from runway threshold (from 0 to 1000 m) while an arriver was on approach. The taxier was required by rule to clear the exit hold line before the arriver's nose crossed threshold. However, the hold line provided sufficient margin that a small violation posed minimal risk of collision. The hold lines were assumed to be 85.34 meters from the centerline of the runway.

In this Section, it is shown that an alerting system can prevent almost all collisions if it provides alerts to both aircraft or to the taxier. Alerts issued to the arriver were less effective; alerts could not be issued before the taxier is sure to cross the entry hold line, but due to a blunder this may happen after the arriver has crossed threshold and can neither go around nor stop before the intersection.

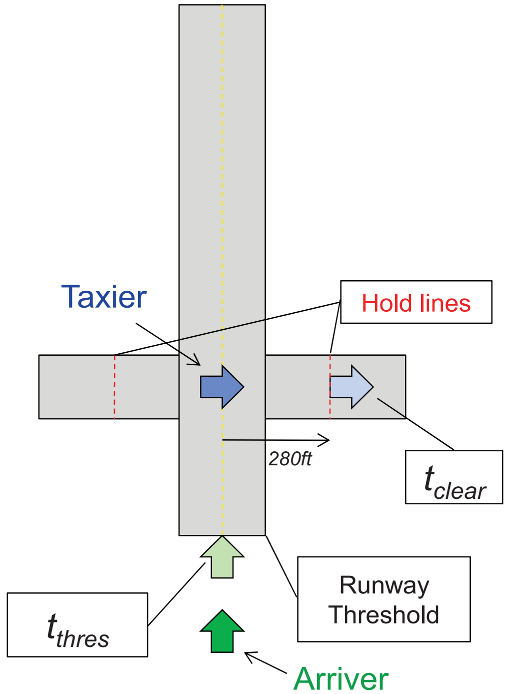



**Figure 8. Taxi Crossing Arrival Runway Scenario**

### 6.2.2 Scenario Model

The taxier was modeled with a constant-velocity trajectory along the center of the taxiway. Position and velocity measurements were simulated as the true value plus a random error, as discussed in Section 6.1.3. Figure 9 shows these measurements for a single encounter.

The arriver was modeled as a series of three phases, shown in Figure 10. The first phase was a constant-speed final approach. When the aircraft reached the touchdown point, the braking phase began. Braking was modeled as constant deceleration. Finally, upon reaching a target rollout speed (rollout phase), motion was again constant-velocity. Speed and deceleration parameters were chosen randomly for each encounter, but remained constant throughout each individual encounter.

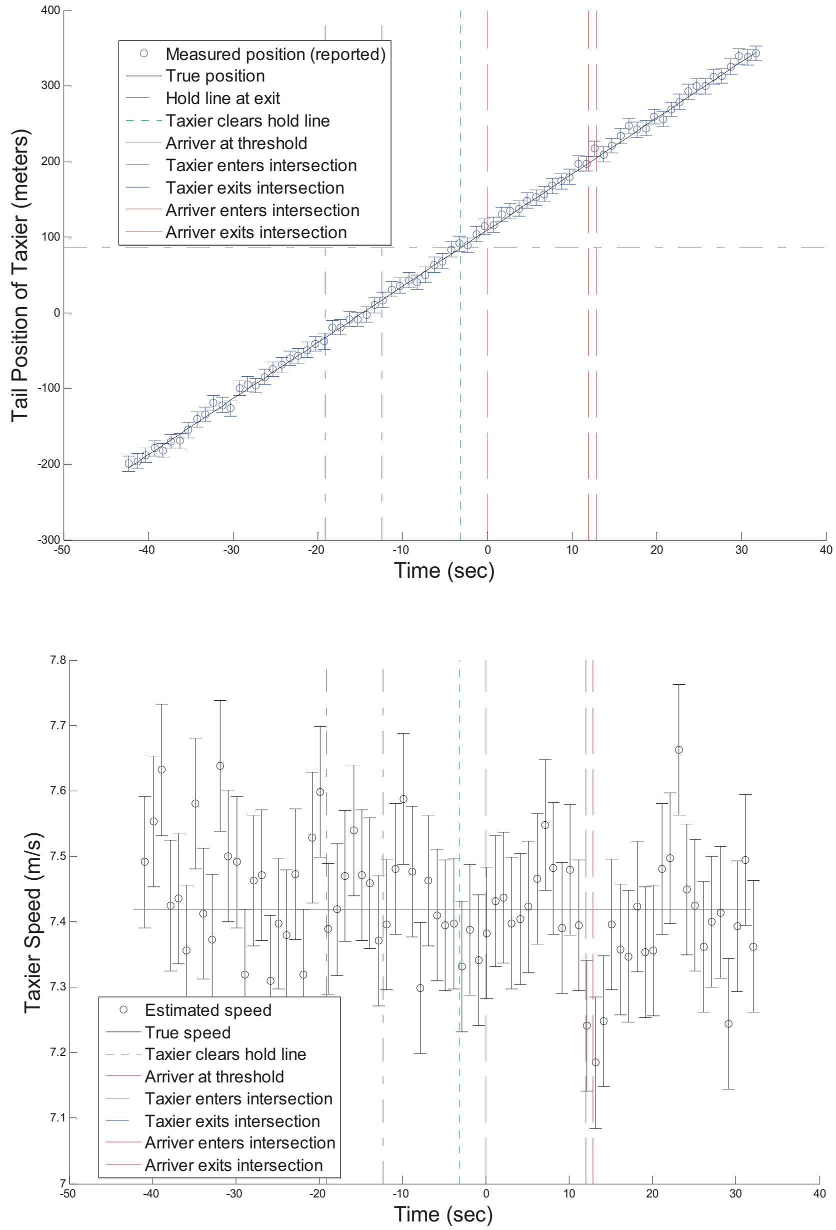



**Figure 9. Measurements of Taxier's Position (top) and Speed (bottom) as a Function of Time for a Single Encounter**

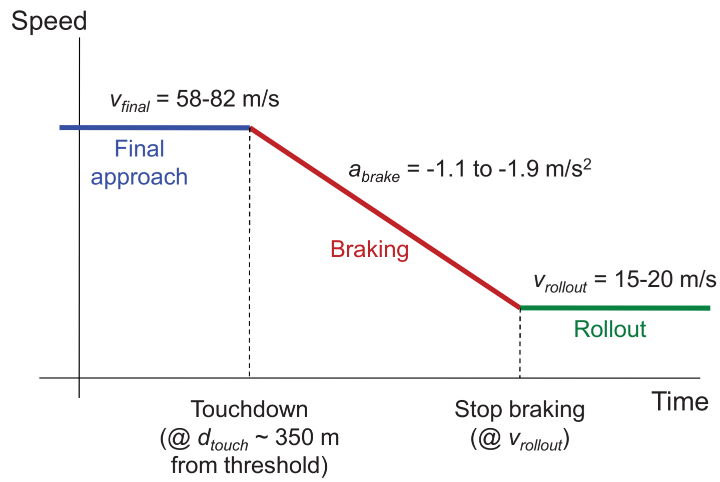



**Figure 10. Arriver Trajectory Model**

Although the arrival model made the simplifying assumption that braking deceleration was constant, it was sufficient to demonstrate the significant features of this scenario and to evaluate the effectiveness of a feasible alerting system. As discussed below, the alerting system does not rely on the assumptions of constant speed deceleration; it allows for fluctuations in these values when computing the uncertainties on its estimates.

Position and velocity measurements were simulated as the true value plus a random error, as discussed in Section 6.1.3 (and identical to the process for the taxier). Figure 11 shows position measurements and velocity estimates derived from the individual measurements for a single encounter.

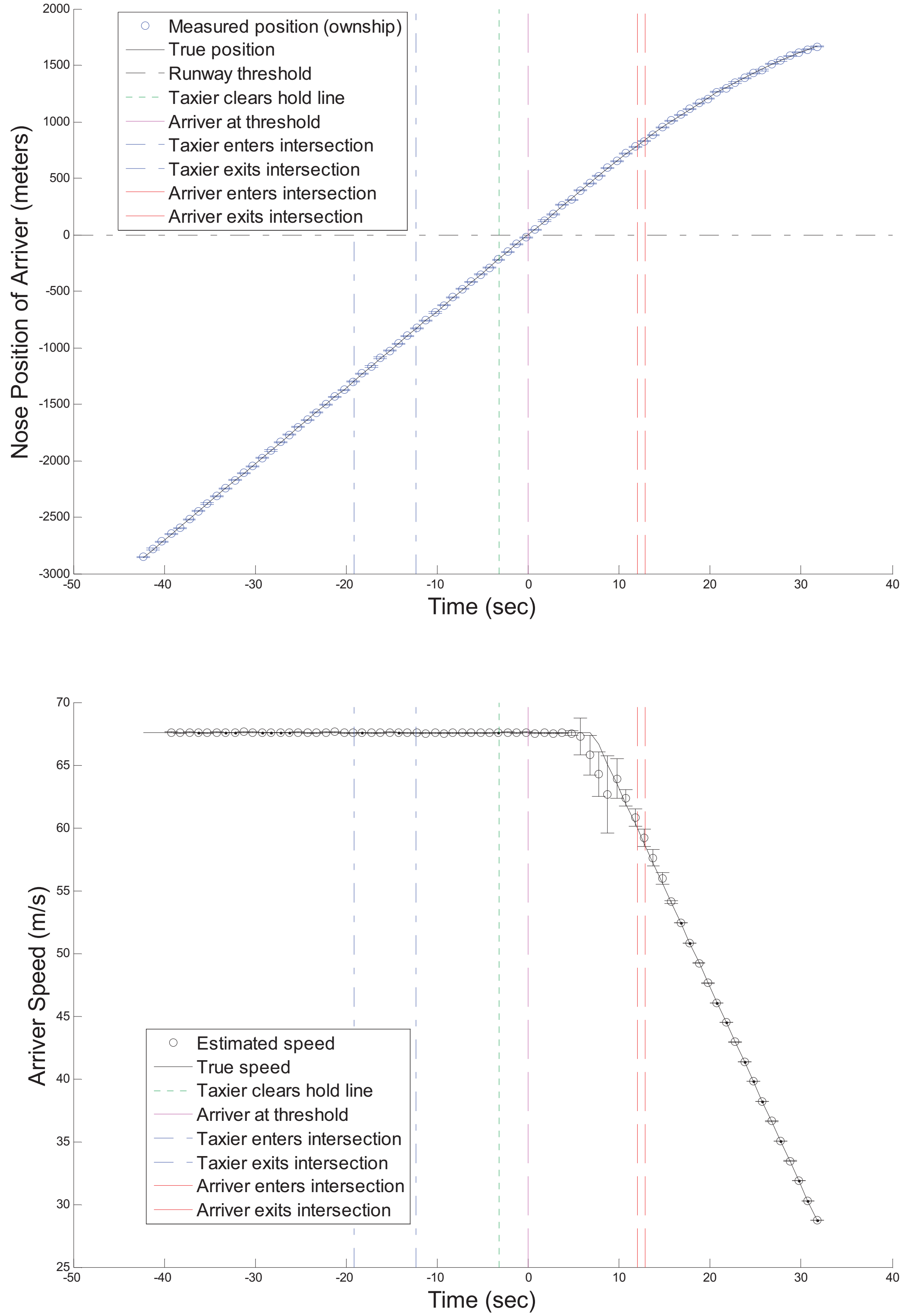



**Figure 11. Measurements of Arriver's Position (top) and Estimates of its Speed (bottom) as a Function of Time for a Single Encounter**

### 6.2.3 Collision Risk With and Without an Alert

The collision risk in each encounter was modeled if no alert was issued or if one or both aircraft received alerts. These risk values were used to evaluate the effectiveness of an alerting system (the fraction of collisions that it prevented).

Collision risk in the absence of an alert was determined by the scenario parameters, which defined the trajectories of the two aircraft. If both aircraft were in the intersection at the same time, a collision was very likely. If they never occupied the intersection at the same time, a collision was very unlikely.

The intersection was defined previously in Section 6.1.2 as follows: for each aircraft, the wingtips swept out two parallel lines, and the wings swept out the region between those lines. The intersection was where the regions for the two aircraft overlapped, as illustrated previously in Figure 7. An aircraft entered the intersection when its nose, wingtip, or tail entered this overlap region, and it exited when every part of it cleared the region.

A safety distance margin was defined as Aircraft A's distance of closest point of approach to the intersection while Aircraft B occupied it, or vice versa. This margin was positive if A stayed clear while B was inside, and negative otherwise, as shown in Figure 12. Large positive values indicated a large safety margin, and negative values indicated that a collision was nearly certain.

The transition from near-certainty of collision to near-certainty of safety was captured with a collision risk function that depended on the safety distance margin. This function was introduced to represent the transition from safe to unsafe separation in a way that reduces artificial edge effects in a computationally simple way. Beginning the transition from zero risk to finite risk at a margin of 10 meters is consistent with past FAA practice in configuring safety logic, where separations less than 35 feet were considered unsafe. The remaining points were chosen based on the assumption that the risk of collision is not 100% at the first contact between the rectangular outlines chosen to represent aircraft extent. Also, it represents the possibility of deviations from the assumed motion model (constant-speed or constant-acceleration depending on the scenario) to represent extreme evasive maneuvers. Figure 13 shows the function with the parameters used for all scenario models. At very negative values, the probability of collision was 100%, while at large positive values it was 0%. Between these regimes there was a smooth transition with a collision probability between 0 and 1.

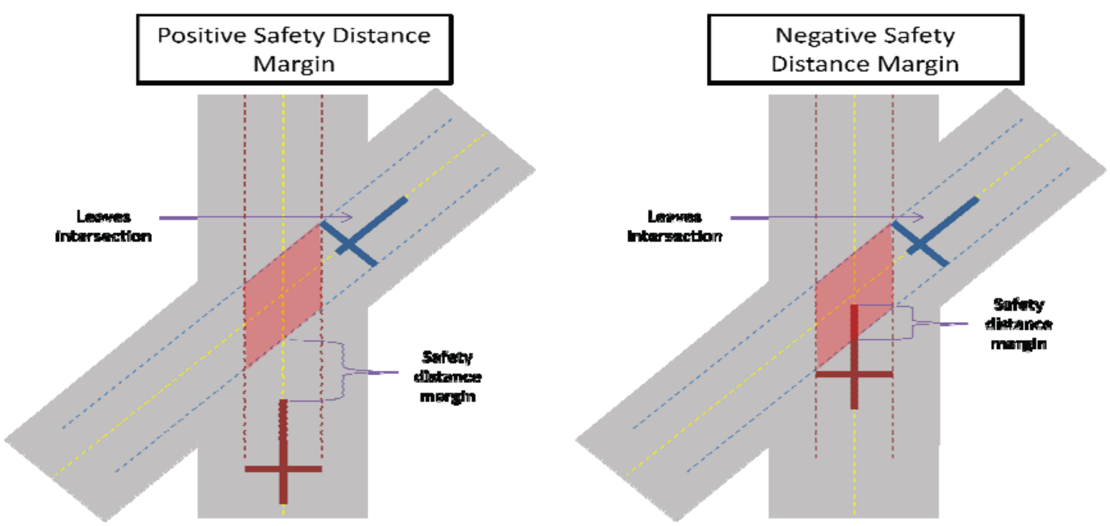



**Figure 12. Definition of Safety Distance Margin**

The collision risk for a particular encounter was determined by first calculating the safety distance margin based on the aircraft trajectories (as determined by the scenario parameters), and then calculating the collision risk from the function in Figure 13.

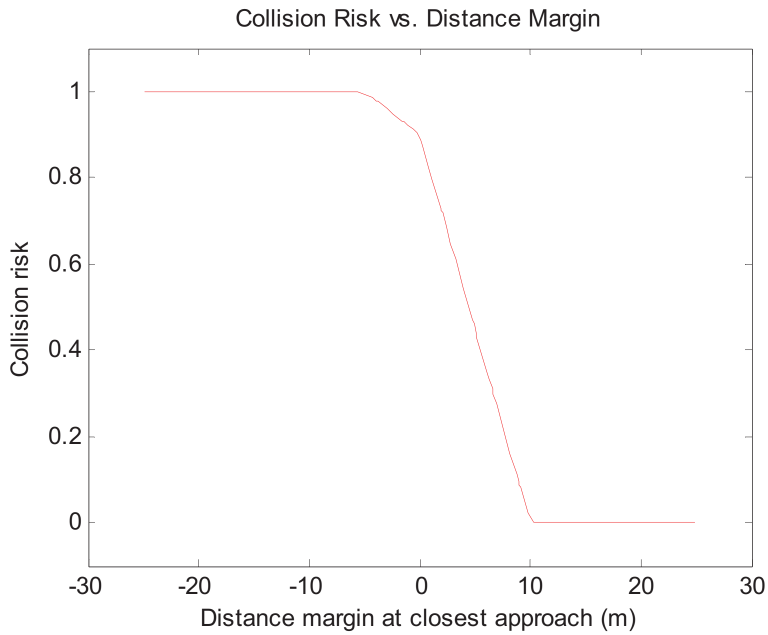



**Figure 13. Collision Risk as a Function of Safety Distance Margin, Capturing the Transition from Zero Collision Risk to Near-certainty of Collision**

When an alert was issued, collision risk was determined from the scenario parameters and the time at which the alert was issued. An alert issued by the ground system was first delayed by a latency of 0.5 seconds to account for transmission to the aircraft, whereas, an on-board alert suffered no delay before it was presented in the cockpit. After the alert was presented, a random pilot response time was added. This time was drawn at random from a log normal distribution, as discussed in 5.3.1. After the response time had passed, the pilot began a resolution maneuver. The probability of success depended on the type of maneuver, the time at which it began, and the other parameters of the scenario.

An alert issued to the taxier may instruct the pilot to either halt before the intersection or to expedite the crossing in order to exit sooner. To evaluate the value of an alert, the collision risk was calculated under either action. The trajectory was modified such that the pilot initiated either braking or acceleration at the time when the response began, and collision risk was calculated using the two alternative trajectories. The system and pilot were assumed to choose the action that produced the lowest collision risk; the lowest risk was then considered to be the outcome of that scenario.

An alert to the arriver may occur in either of two phases. If it is given after touchdown, it orders the pilot to brake to a stop as soon as possible. The effectiveness of such an alert was evaluated in the same way as for the taxier. Braking began after the response time had elapsed, and collision risk was calculated using the modified trajectory. If the alert was given before the aircraft crossed the threshold, it was presumed to trigger a go-around. The probability of success was taken to be a function of the time when pilot response began. If the go-around was initiated well before threshold, it was nearly certain to successfully avoid the collision. After threshold, a go-around alert had very little value. In between was a transition. The go-around procedure was modeled with the function shown in Figure 14. The collision risk was the product of the alert value determined from this function and the collision risk in the absence of an alert. The role of vertical separation in preventing collision was not addressed explicitly, but the

effect was folded into the dependence of successful resolution on time before threshold when resolution action began (after the modeled pilot reaction time has elapsed).

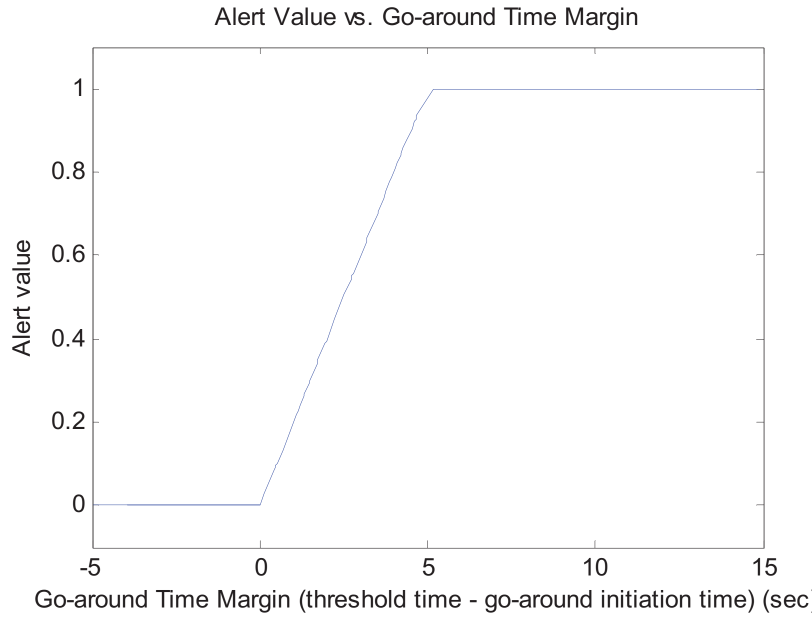



**Figure 14. Value of Alert Ordering a Go-around, as a Function of the Time when Pilot Reaction Begins**

The value of an alert was defined as the probability that it averted a collision if one could occur. It was calculated as:

Alert value = 1 – (probability of collision with alerting system)/(probability of collision without alerting system)

Then the probability of collision was:

(Probability of collision with alerting system) = (1- alert value)*(probability of collision without alerting system)

If both aircraft received alerts, then a collision occurred only if both alerts failed to produce a successful avoidance maneuver. Assuming the success of two aircraft's maneuvers were independent, then

(Probability of collision with alerting system) = (1- taxier alert value)*(1 - arriver alert value)*(probability of collision without alerting system)

### 6.2.4 Projected Times and Margins

The alerting system required projection of future states from the current state, and estimates of the uncertainties on the future states. In this section the process used to project future states is described.

Projections suffer from two types of uncertainties, as discussed in Section 6.1.5. First, uncertainties in measurements of the current state propagate into the estimates of future state. Second, no measurement can predict future pilot behavior, and so the model used to project future states may not be accurate.

For example, consider an arriver currently on final approach. The aircraft's current position and velocity are measured with some uncertainty. To predict, for example, the time when the aircraft reaches threshold, the average speed until that time must be projected. Since speed may fluctuate, that average speed will have a higher uncertainty than the uncertainty on the current measured speed. Therefore, when

estimating time to threshold, an uncertainty on speed was included that accounted for the typical magnitude of speed fluctuations.

To project the time when the arriver will enter an intersection located some distance from threshold, it must be assumed where the aircraft will touch down and how hard it will brake. Since these quantities are not known, the estimate of the time entering the intersection will be dominated by their uncertainty.

Although the truth-level trajectories feature constant velocity or acceleration, the future state projection process did not assume such simplicity. The uncertainties include the possibility of fluctuations in speed or acceleration, and uncertainty of future pilot behavior.

As each new measurement was received, projected times of different events for each aircraft were calculated. For the taxier, the time of three events was calculated: nose entering intersection, tail exiting intersection, and tail clearing exit hold line. For the arriver, the time of three events was also calculated: nose crossing threshold, nose entering intersection, and tail exiting intersection. These estimates are shown as a function of time in Figures 15a-15c . For each estimate, the measurements converged on the true value (shown as one of the horizontal lines), and the error bars cover a range that includes the true value. The uncertainties (shown by the error bars) decreased as the event time occurred; that is, the estimates were more precise when projected over a shorter period of time.

At later times, more information was available and the projections occurred over shorter time spans, so estimates were more precise (as indicated by the smaller error bars). Plots on the left are for the taxier; from top they are projections of intersection entry time, intersection exit time, and time clearing the exit hold line. Plots on the right are for the arriver; from top they are projections of time crossing threshold, intersection entry time, and intersection exit time.

The projected times were used to determine the time margin between events. For example, a rules violation occurred if the arriver's nose crossed threshold before the taxier's tail cleared the exit hold line. Therefore, a predicted "rules margin" was calculated as the time difference between these events. A positive margin indicated that the taxier cleared in time, and no rules were violated. A negative margin indicated a rules violation. Figure 16 shows an example of how the rules margin estimate evolved, increasing in precision over time. The alerting algorithm used the estimated rules margin, and its uncertainty, to determine whether it was likely that the encounter violated an operational rule.

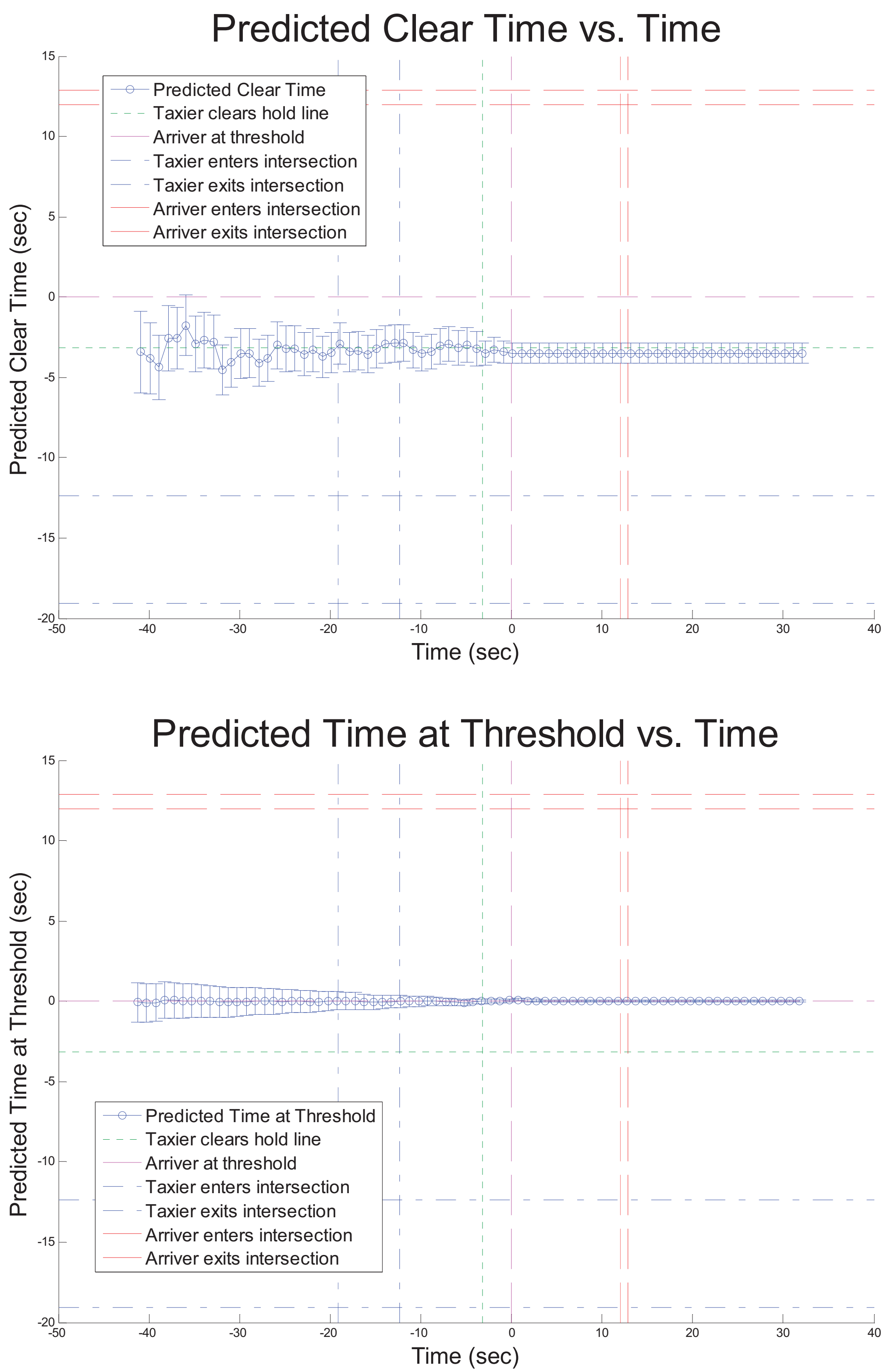
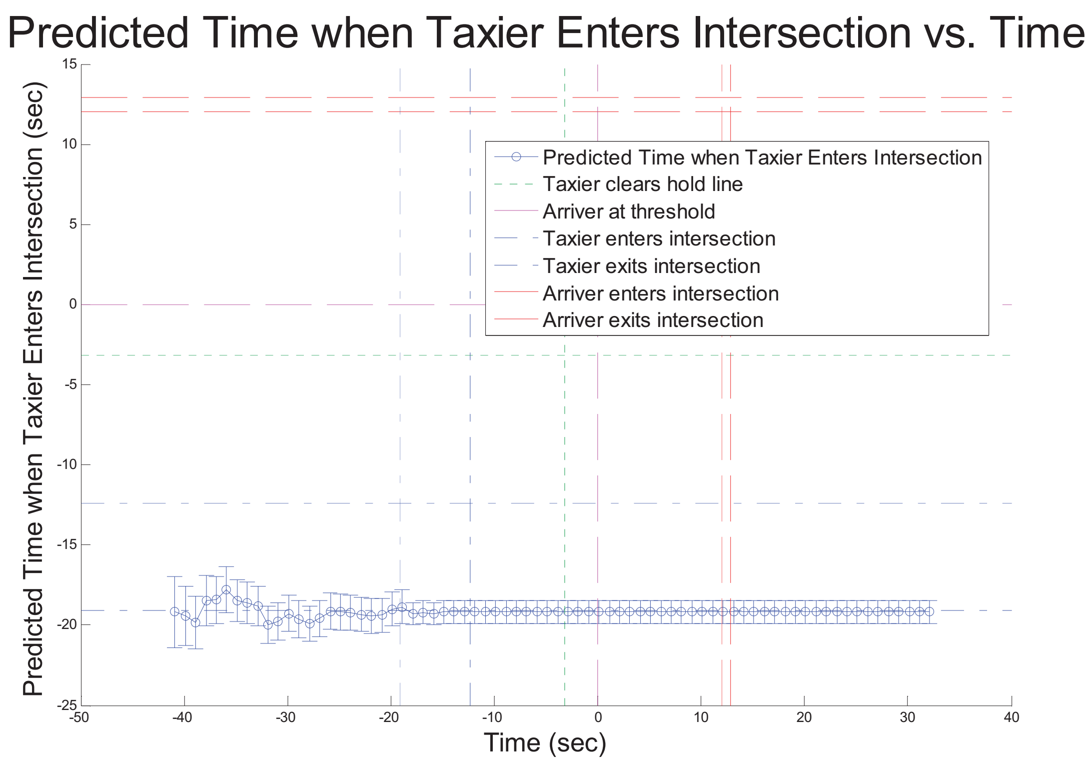



**Figure 15a. Projected Times of Taxier Clearing Intersection, and Arriver Crossing Threshold, as a Function of the Time of Estimation**



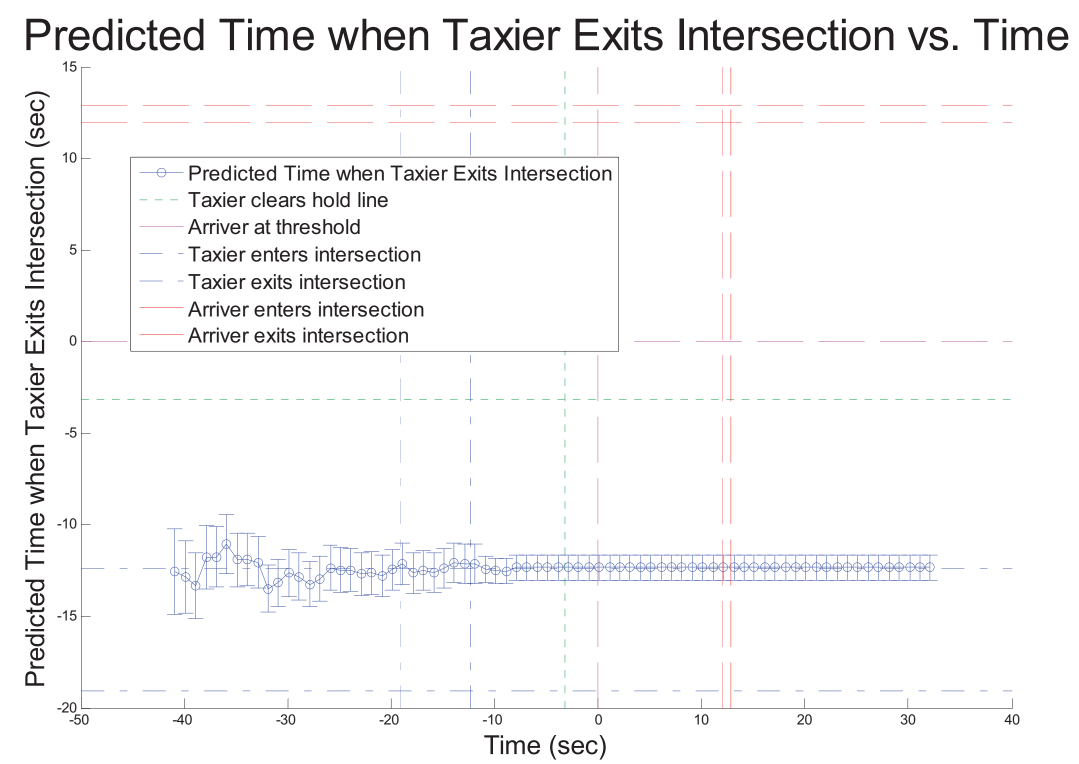
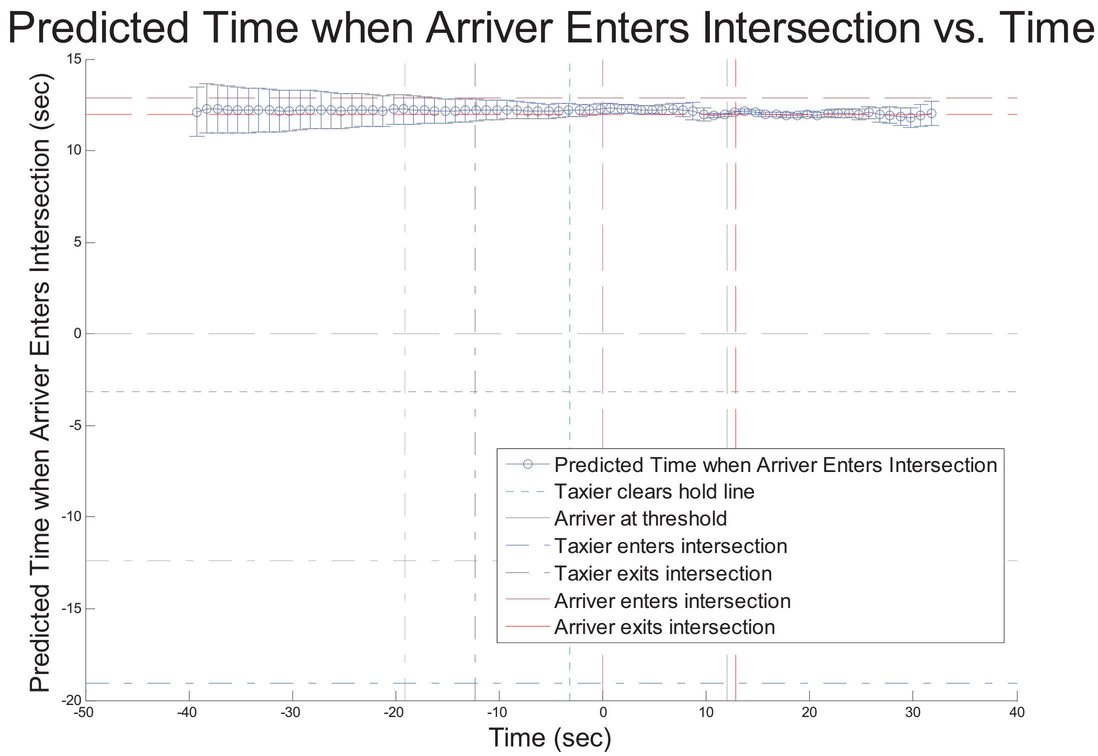




**Figure 15b. Projected Times of Taxier Entering and Exiting Intersection, as a Function of the Time of Estimation**



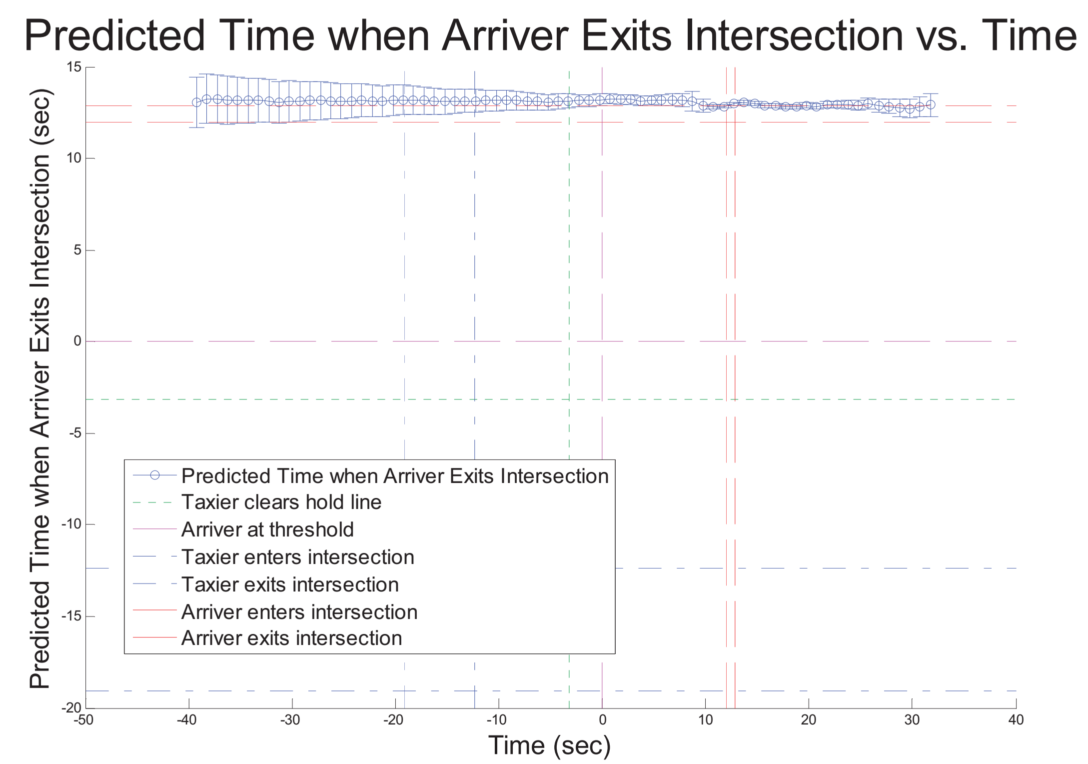




**Figure 15c. Projected Times of Arriver Entering and Exiting Intersection, as a Function of the Time of Estimation**

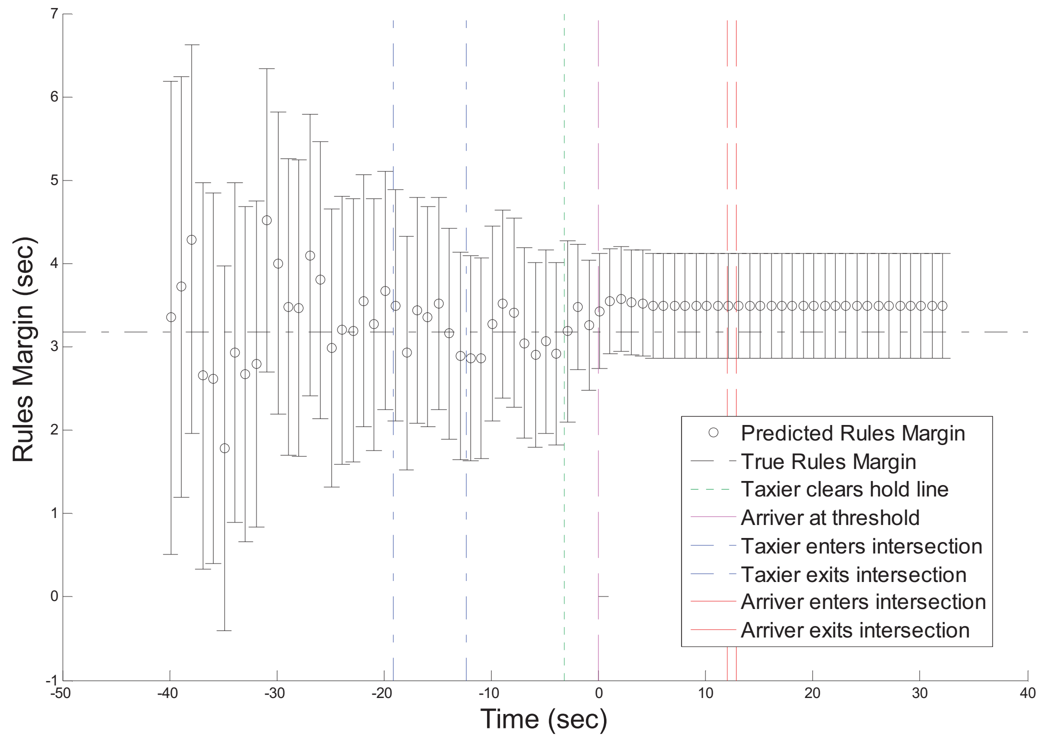



**Figure 16. Rules Margin Estimates as a Function of Estimation Time**

As time progressed the estimates became more precise. In this example, the taxier cleared the hold line 3.2 seconds before the arriver crossed threshold, as indicated by the horizontal dashed line.

Also significant to the alerting algorithm is the question of whether the two aircraft were likely to be in the intersection at the same time. For this purpose, two safety margins were evaluated. The first tested whether the taxier exited the intersection before the arriver entered. For this test, a safety margin was computed that was the difference between the projections of these two times. The second test was for the alternative hypothesis that the arriver exited before the taxier entered. A second safety margin was computed from these projected times. If either of the two margins was positive, then no collision occurred. If both were negative, then both were in the intersection at the same time, and a collision was likely. Therefore, the alerting algorithm issued an alert if there was significant risk that both were negative.

In the example shown in Figure 17, the arriver entered the intersection about 24 seconds after the taxier exited (top plot), indicating that there was no collision risk. The bottom plot, showing the safety margin under the false assumption that the arriver preceded the taxier, shows a negative margin, but a safe operation requires only that one of the two margins is positive. In a high-risk encounter, both margins would be negative.

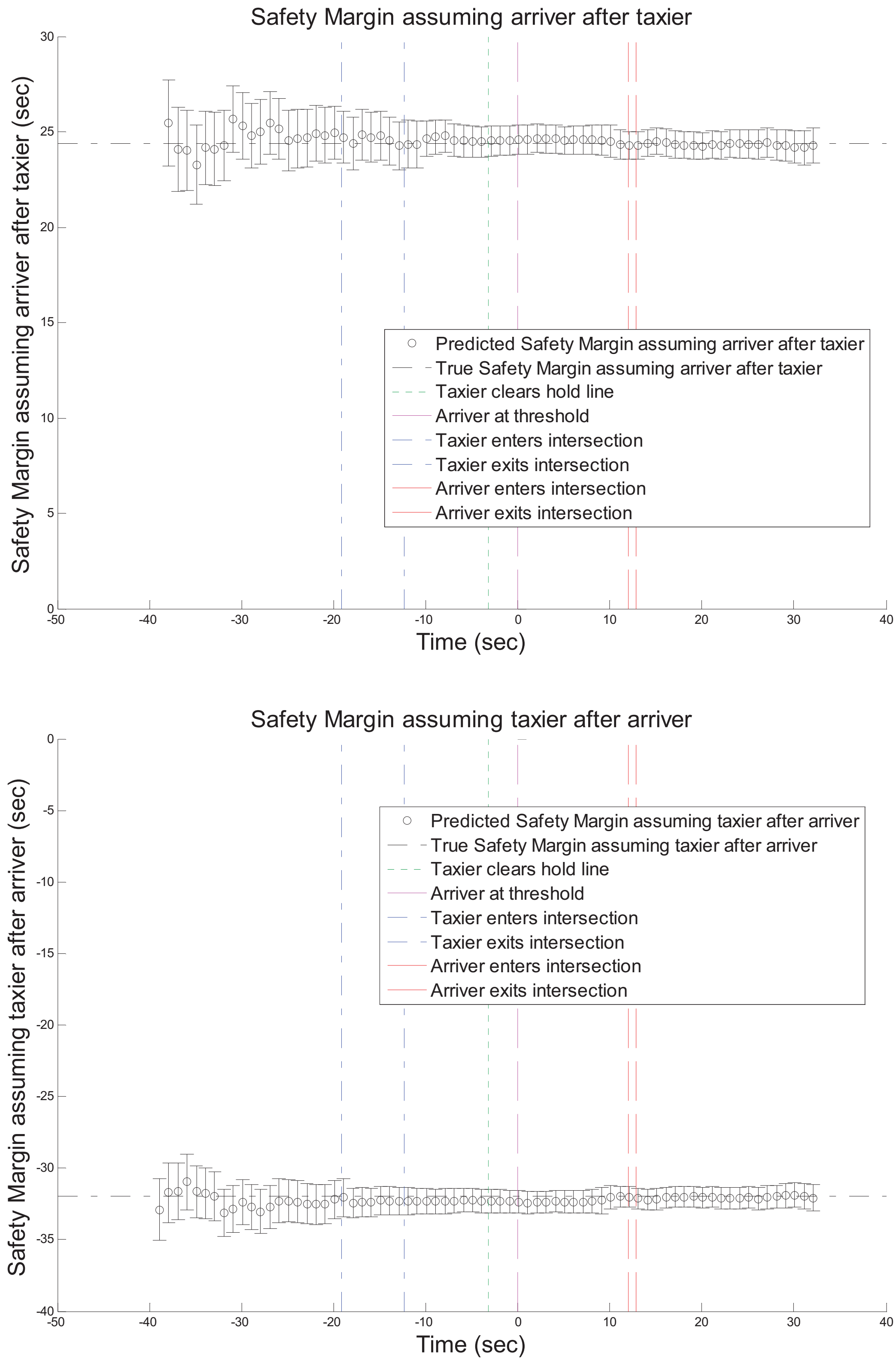



**Figure 17. Safety Margin Estimates as a Function of Estimation Time**

### 6.2.5 Alerting Algorithm

The alerting algorithm compared various measured and projected quantities to threshold values, and issued an alert if all quantities passed those thresholds. The quantities and thresholds were chosen to satisfy three broad requirements:

- An alert would be issued only if the potential threat required a prompt avoidance maneuver, and if that maneuver was feasible. For example, an arriver would almost certainly execute a go-around if the maneuver began at least ~30 seconds from threshold. Therefore, there was no need to issue alerts before that time. At the other end of the range, there was no reason to issue a go-around alert after touchdown.
- An alert would be issued only if there was high confidence that an operational rule had been violated. This translated to a requirement that there was high confidence that the rules margin was negative.
- An alert would be issued only if there was a significant risk of collision. Here "significant" meant that the chance of collision was greater than, say, one or a few percent. This means that an alert was not issued unless there was high confidence that at least one of the two safety margins was positive.

Figures 18a-18d show the alert quantities and thresholds for an example encounter in which an alert was generated for the arriver during final approach.

Note that this encounter is different from the ones used to generate earlier plots, as it features a higher collision risk. The red X's mark times when an alert was issued (because all quantities passed their respective thresholds). The top plot of Figure 18a shows that the taxier was past the entry hold line, or could not stop before it. The bottom plot shows that the taxier had not yet passed the intersection exit. The next two plots (Figure 18b) show that the arriver was less than 30 seconds from threshold but not yet past threshold. The next two (Figure 18c) show that the two aircraft were in the intersection at the same time. The final plot (Figure 18d) shows that a rules violation was likely (that the taxier will fail to clear the exit hold line before the arriver crosses threshold).

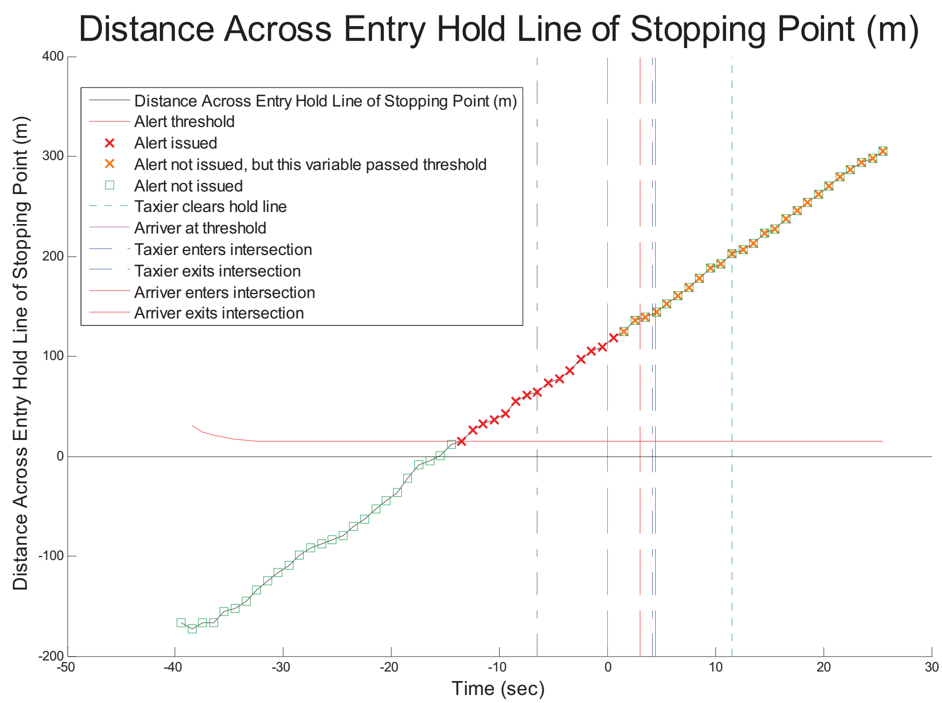
The requirements are formulated in a way that incorporates the uncertainties on the parameters. For the rules margin and safety margin requirements, the margin value was normalized by dividing by its estimated uncertainty. The first requirement for generating an alert was that the scaled rules margin was less than -2, indicating that the system was confident that a rules violation was occurring. The second requirement was that the scaled safety margin was less than +2, indicating that the system was *not* confident that collision risk was insignificant. That is, the system suppressed the alert only if it was confident that there was a positive safety margin. These criteria were chosen as a simple model of alert behavior constrained by unwanted alert requirements; the parameters assumed would be modified in an operational system to meet specified design criteria.

An alert could also be issued to the arriver after touchdown. After touchdown, the alert criteria were the same except that the position was required to be after, rather than before, threshold. It was determined whether the aircraft had touched down by measuring weight on wheels. If an alert was generated after threshold but before touchdown, it was not presented in the cockpit until 1 second after touchdown (whether the alert was generated on-board or by an external system).

For the taxier, the same alert criteria were used, except that there was no requirement on the arriver's position relative to runway threshold. An alert may be issued to the taxier at any point after the arriver was 30 seconds from threshold and before it passed through the intersection.

For the arriver, the most significant requirement affecting alert effectiveness was the requirement that the taxier could not stop before the entry hold line. If the intersection was some distance down the runway, a

blundering taxier could cross this line after the arriver had touched down and could no longer go around, but before the arriver reached the intersection. In this case the arriver could receive an alert to halt, but if the intersection was not too far down-runway there may not be enough distance to stop. In these scenarios, an alert issued to the arriver would not be effective. This is discussed further below.



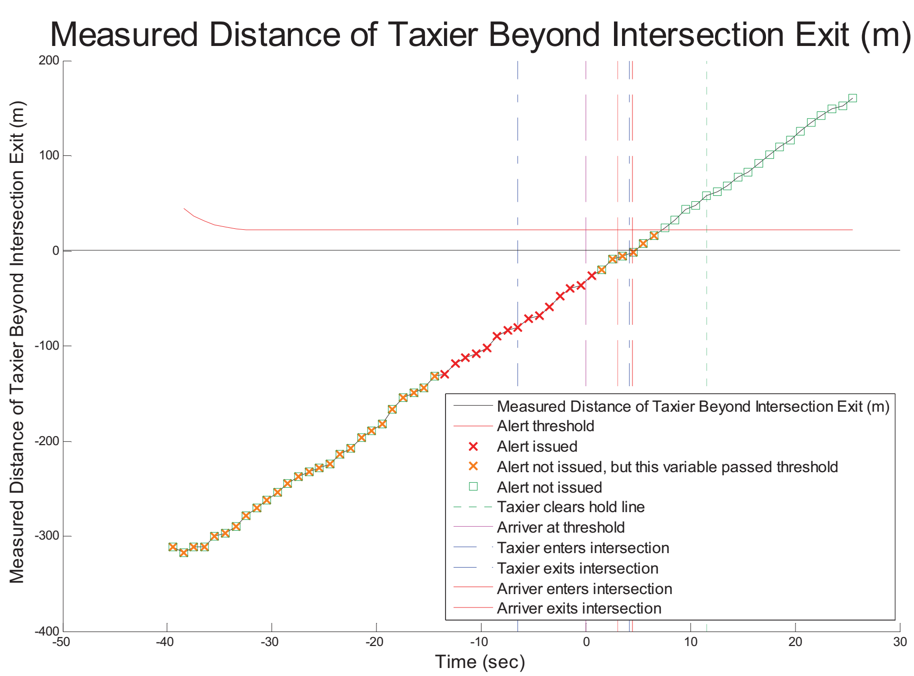
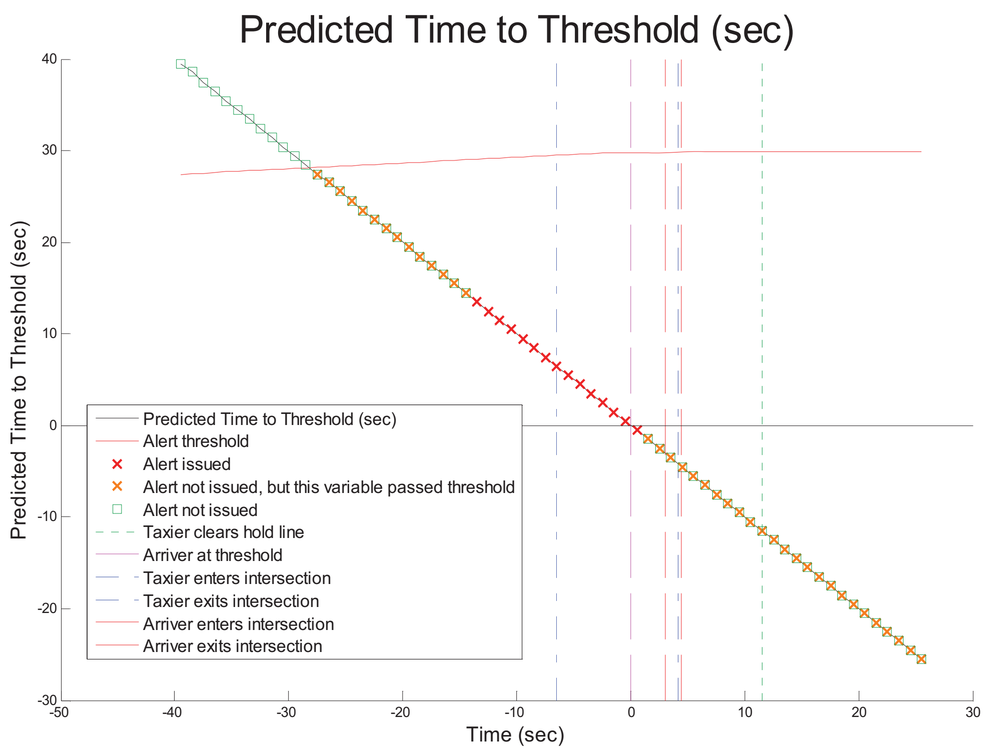




**Figure 18a. Alert Quantities, Thresholds, and Values for an Example Encounter**



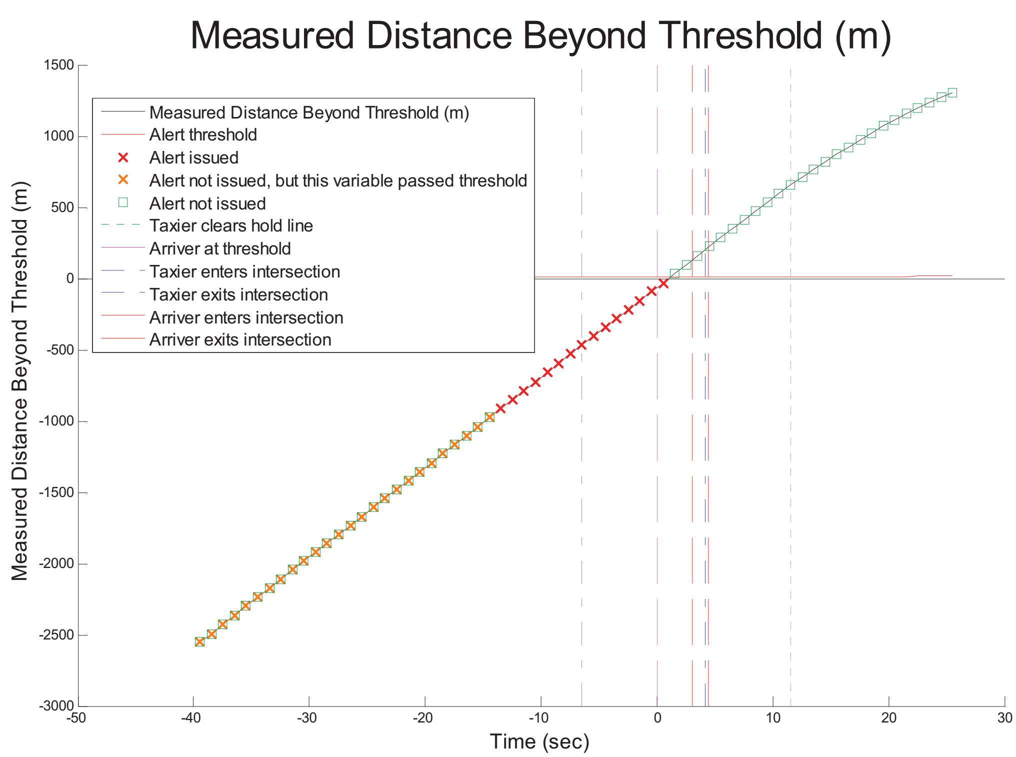
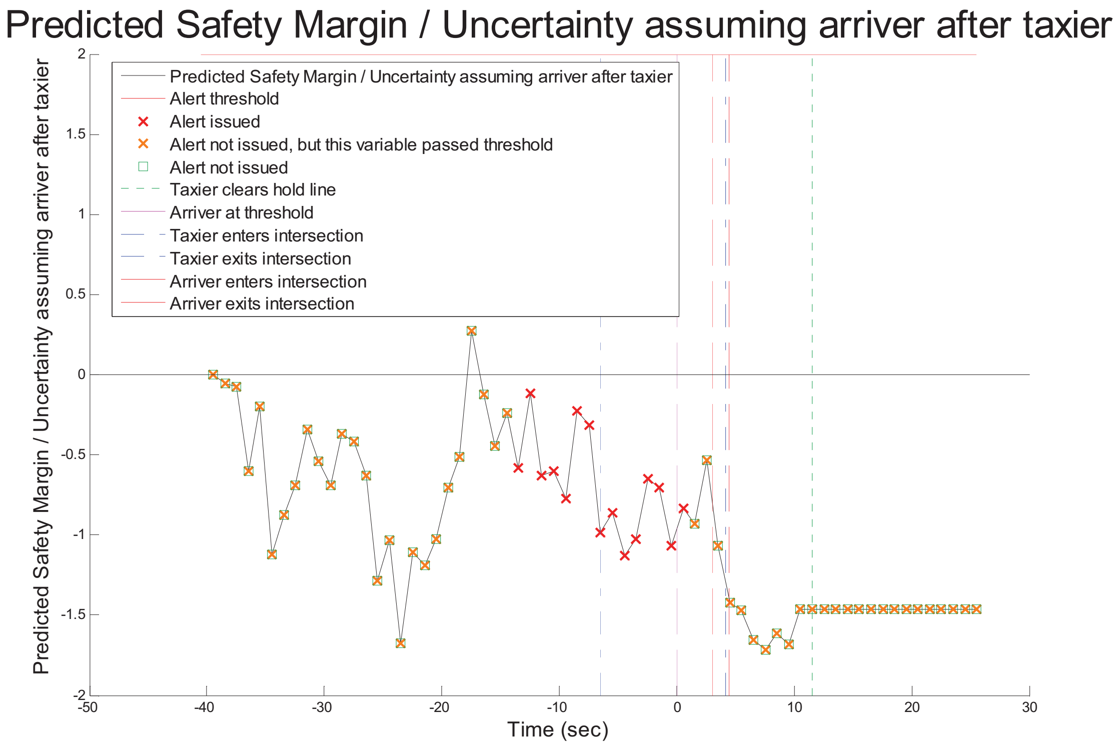




**Figure 18b. Alert Quantities, Thresholds, and Values for an Example Encounter**



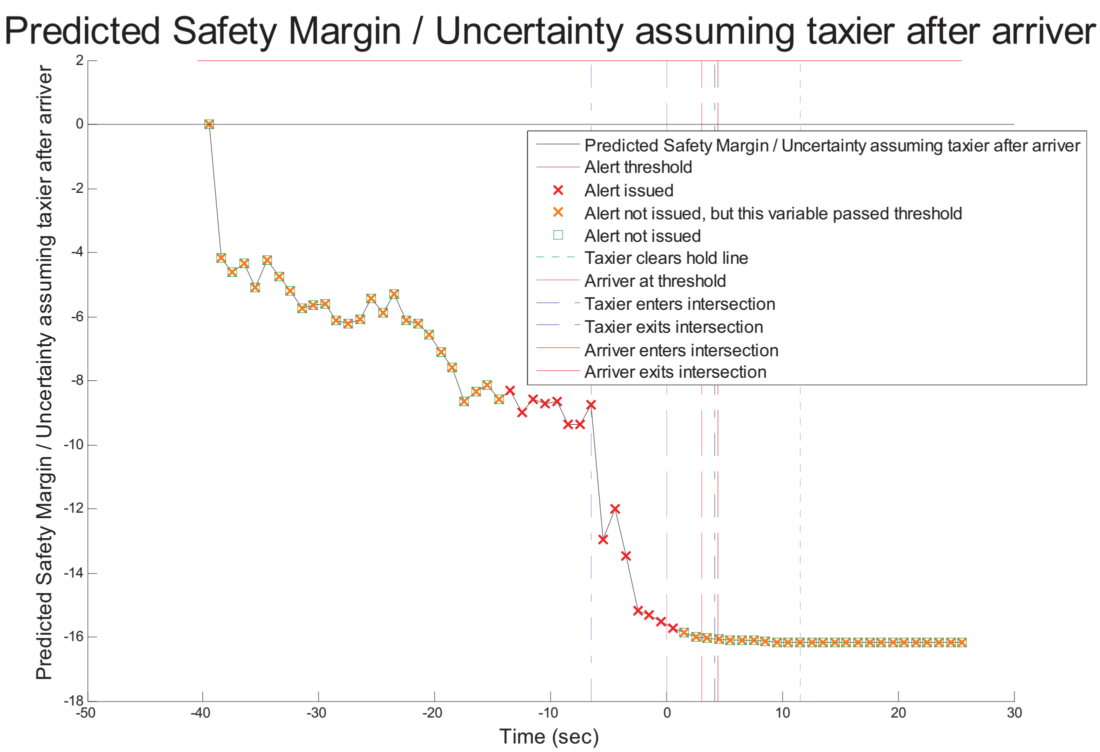




**Figure 18c. Alert Quantities, Thresholds, and Values for an Example Encounter**

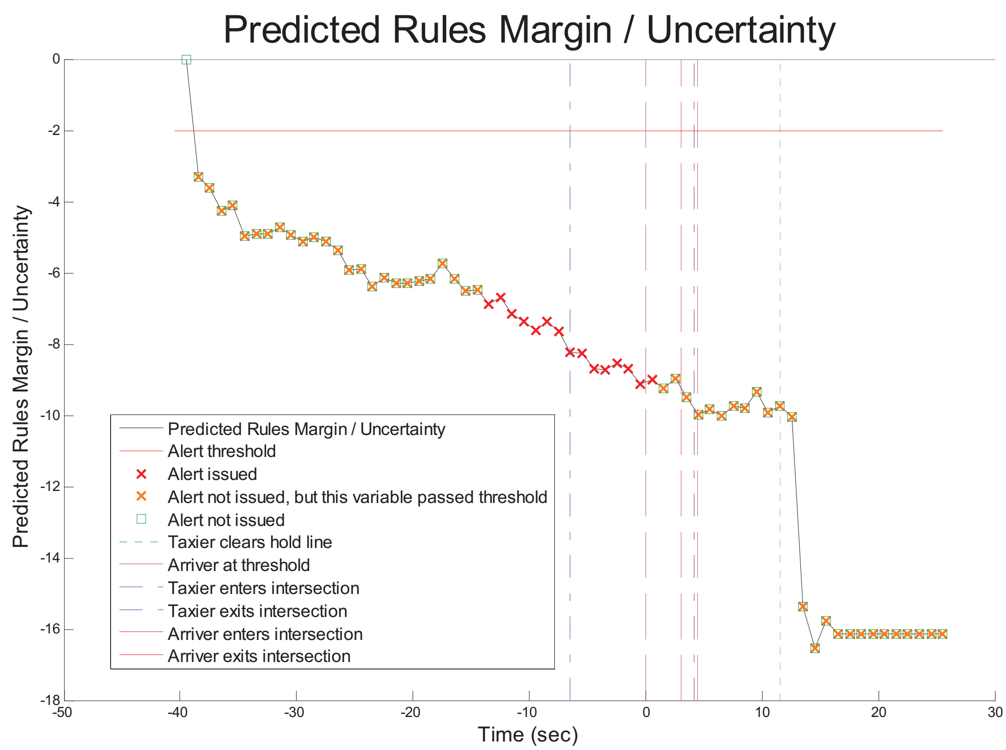



**Figure 18d. Alert Quantities, Thresholds, and Values for an Example Encounter**

### 6.2.6 Nuisance Alert Rate

The nuisance alert rate was evaluated in an ensemble of encounters taken to represent normal operations. In this ensemble, it was assumed that the controller issued a clearance for the taxier to cross the runway, aiming to achieve a 5-second margin between the taxier clearing the exit hold line and the arriver crossing threshold. The actual margin varied due to uncertainties in the taxier's response time in complying with the clearance, the taxier's actual speed, and the arriver's actual time at threshold. Figure 19 shows the distribution of the actual "rules margin" (left plot). Note that this assumed ensemble contained an unrealistically high fraction of encounters in which a rules violation occurred. This was actually a more demanding test of the nuisance alert rate. If the rate was acceptably low in this ensemble, it would be even lower in a more realistic one.

The actual safety margin is a function of the rules margin and the distance from runway threshold to the intersection; its distribution in the ensemble is also shown in Figure 19 (right plot). Even though many encounters included a rules violation, none of them were severe enough to pose a collision risk.

An ensemble of 400,000 encounters was simulated with a ground-based alerting system. None of these encounters generated an alert. Based on a binomial distribution, this shows that the nuisance alert rate was less than $0.9 \times 10^{-5}$ at 95% confidence. Thus it has been validated that the nuisance alert rate was acceptably low for the ground-based alerting system. While this test was not performed for on-board alerts, there is no reason to suspect a significant difference.

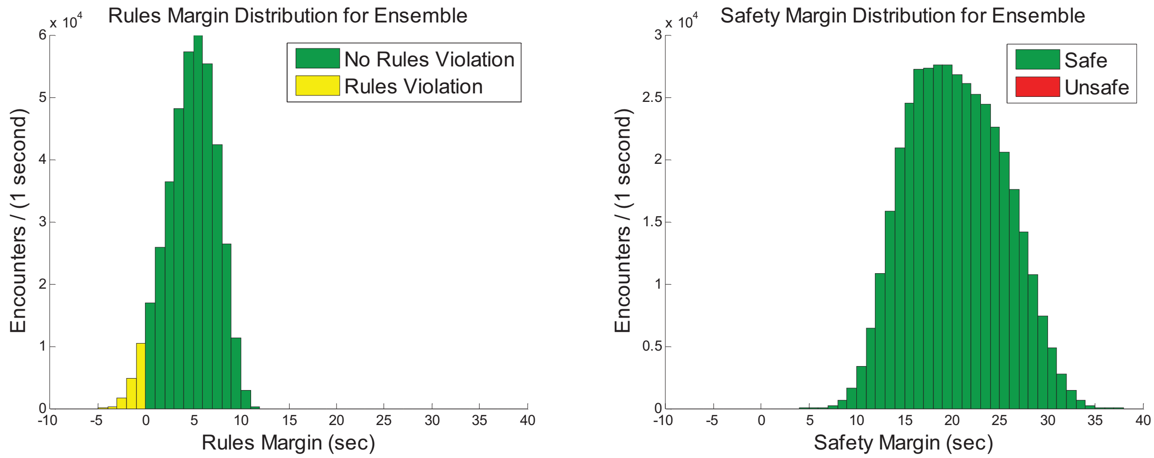



**Figure 19. Rules Margin (left) and Safety Margin (right) Distributions for Ensemble used to Evaluate Nuisance Alert Rate**

### 6.2.7 Alert Effectiveness

The effectiveness of the alerting system was evaluated by comparing collision rates with and without the alerting system, as discussed in Section 6.2.3.

Collision risk was primarily determined by the time when the taxier initiated the crossing, relative to the arriver's landing time. A blunder must occur at "just the wrong time" to result in a collision. This is illustrated in Figure 20, which shows collision risk as a function of crossing initiation time for a given distance (500 m) from runway threshold to taxiway. The uppermost, red line (with triangles) shows the collision risk without an alerting system. For a range of blunder times, collision was very likely, and outside that range collision was very unlikely. The other lines in the plot show the collision risk with alerts issued to the arriver, taxier, or both.

Effectiveness depended strongly on whether alerts were issued to the arriver, taxier, or both, and on the distance from runway threshold to the intersection. As shown in Figure 21 for the 500 m threshold-to-intersection case, alerts to the taxier were very effective, and alerts to the arriver only were ineffective when the blundering taxier began the crossing at a later time relative to arriver crossing threshold (leaving too little time to execute a missed approach). In Figure 21, these conditions are further highlighted showing the fraction of collisions averted by the alerting system as a function of who received alerts and of the distance to the intersection.

Alerts issued to the arriver were not effective at intermediate distances (~800 m). In these encounters, the taxier crossed the entry hold line too late for a go-around alert, but the arriver could not brake to a stop before the intersection. At smaller distances, the taxier must, in order to be a danger, begin the crossing while the arriver was still airborne and capable of going around. At larger distances, the arriver can brake to an emergency stop after touchdown, stopping before the intersection.

Alerts issued to the taxier were effective at all distances, as they could instruct a blundering taxier to halt before entering the intersection. Even if the taxier was past the entry hold line, it could still halt prior to entering the intersection. Such an event would technically be classified as a runway incursion, but it would pose little collision risk.

Figure 21 shows that alerts were more effective when issued on-board than when issued by a ground-based system. The main reason for this is that the ground-based system incurred additional latency for transmission of measurements from aircraft to ground, evaluation of the alert criteria, and transmission of alerts from ground to aircraft. With this latency, alerts would be presented later in the cockpit.

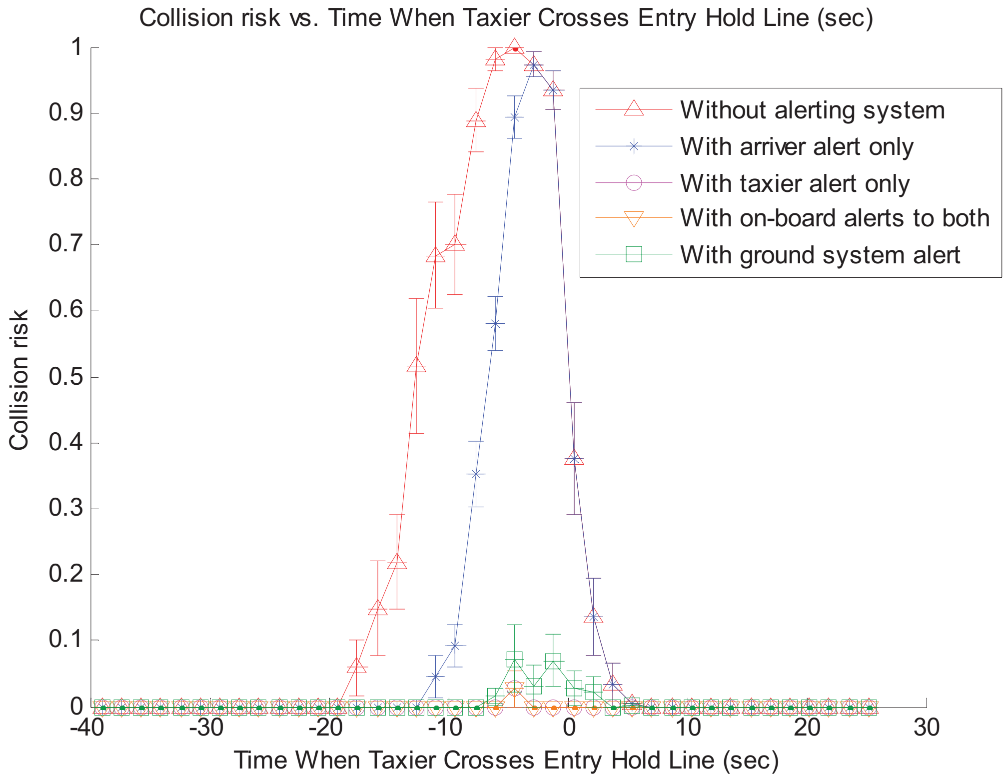



**Figure 20. Collision Risk as a Function of Time when Taxier Crosses Entry Hold Line**

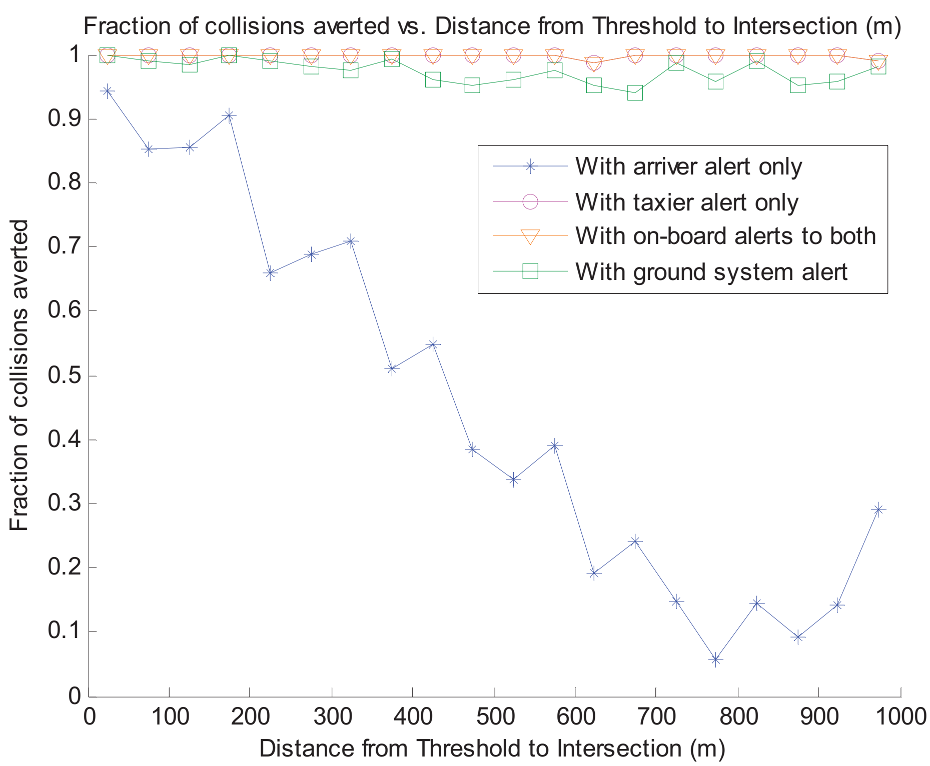



**Figure 21. Collision Risk as a Function of Distance from Threshold to Intersection**

#### 6.2.7.1 Dependence on Response time

Response times were modeled as a random draw from a log normal distribution for each aircraft. The arriver's response time distribution had a median of 3 seconds, and the taxier's had a median of 2.5 seconds.

To explore the sensitivity of alert effectiveness to response time, all response times were halved and doubled and re-evaluated for alert effectiveness. Table 5 shows the fraction of collisions averted as response time varies. The results were sensitive to response time, especially for alerts issued to the arriver.

**Table 5. Fraction of Collisions Averted by Alerting as a Function of Response time**

| | Response times x½ | Baseline | Response times x2 |
|---|---|---|---|
| **Arriver Alert Only** | 54.8 ± 1.2 % | 44.3 ± 1.0 % | 27.1 ± 0.9 % |
| **Taxier Alert Only** | 100.0 ± 0.0 % | 99.8 ± 0.1 % | 86.8 ± 0.9 % |
| **Ground-Based Alerts to Both** | 99.9 ± 0.1 % | 97.3 ± 0.4 % | 70.6 ± 1.1 % |

#### 6.2.7.2 Dependence on Position Measurement Precision

A one-sigma position measurement accuracy of 5 m was assumed. To explore the sensitivity of alert effectiveness to this parameter, new ensembles with accuracies of 2.5 m and 10 m were generated. Table 6 shows the fraction of collisions averted as measurement precision varied. There was modest improvement in alert effectiveness as precision improved.

**Table 6. Fraction of Collisions Averted by Alerting as a Function of Position Measurement Precision**

| | 2.5m Precision | 5m Precision | 10m Precision |
|---|---|---|---|
| **Arriver Alert Only** | 51.9 ± 3.7 % | 46.1 ± 4.0 % | 44.8 ± 3.9 % |
| **Taxier Alert Only** | 100.0 ± 0.0 % | 99.6 ± 0.3 % | 98.4 ± 0.8 % |
| **Ground-Based Alerts to Both** | 98.9 ± 0.8 % | 95.8 ± 1.8 % | 93.5 ± 2.0 % |

#### 6.2.7.3 Dependence on ADS-B Velocity Measurement

The alerting algorithm was assumed to have access to an independent ADS-B measurement of velocity, rather than being limited to a velocity estimated from position measurements. The assumed accuracy of this measurement, either 0.03 m/s or 0.10 m/s according to the equipage model described in Section 6.1.3, was much better than the accuracy for velocity derived from smoothing recent position measurements. To explore the sensitivity of alert effectiveness to the availability of this measurement, alert effectiveness was evaluated with and without it. Table 7 shows the results. The high-precision ADS-B velocity measurement did not discernibly improve alert effectiveness.

Although the collision risk and nuisance alert rate did not change when the ADS-B velocity measurement was removed, the alert rate did increase for encounters containing a rules violation but no significant collision risk. With the increased uncertainties, the alert algorithm could not rule out a collision risk in some of these cases, and so it issued more alerts.

**Table 7. Fraction of Collisions Averted by Alerting with and without ADS-B Velocity Measurement**

| | With ADS-B Velocity | Without ADS-B Velocity |
|---|---|---|
| **Arriver Alert Only** | 44.3 ± 1.5 % | 44.0 ± 1.4 % |
| **Taxier Alert Only** | 99.6 ± 0.2 % | 99.6 ± 0.1 % |
| **Ground-Based Alerts to Both** | 97.5 ± 0.5 % | 97.0 ± 0.5 % |

### 6.2.8 Comparison of NextGen Environments

To evaluate safety in the four NextGen environments, the effects of both the alerting system and the situational awareness benefits of the adopted technologies were modeled. The technologies and associated benefits depend on aircraft class (New Transport, Retrofit Transport, or Non-Transport) and environment, as shown in Table 2.

The SA benefits are summarized in Table 8. Non-traffic alerting was assumed to prevent some blunders onto the runway, so if the taxier had this technology some fraction of blunder encounters would never happen. It was assumed that in this case the blunder rate was reduced by 20%. CDTI provided additional SA benefits; either the taxier or the arriver may see the other aircraft and take corrective action before a blunder develops. It was assumed that CDTI reduced the taxier's blunder rate by 80%, and the arriver's rate by 60%. If both aircraft enjoyed SA benefits, the combined effect was multiplicative. For example, if both had CDTI the blunder rate was reduced by a factor of (1-80%)(1-60%) = 0.08. That is, 92% of blunder encounters were prevented by SA.

**Table 8. Situational Awareness Benefits as a Function of Aircraft Class and NextGen Environment**

| | New Transport | Retrofit Transport | Non-Transport |
|---|---|---|---|
| **NextGen 1** | base | base | base |
| **NextGen 2** | CDTI | non-traffic alerting | base |
| **NextGen 3** | CDTI | CDTI | CDTI |
| **NextGen 4** | CDTI | CDTI | CDTI |

The alerting systems available in each NextGen scenario are shown in Table 9. Basic runway alerting included the alerts in the taxi crossing scenario, so alerts were provided to all aircraft in NextGen 3 & 4, and to New Transport in NextGen 2. The fraction of collisions prevented by alerting was evaluated using the simulation discussed above. This quantity was determined for each pair of aircraft classes under each type of alerting. When no alerting was available, the fraction prevented was 0%.

**Table 9. Alerts Available as a Function of Aircraft Class and NextGen Environment**

| | New Transport | Retrofit Transport | Non-Transport |
|---|---|---|---|
| **NextGen 1** | none | none | none |
| **NextGen 2** | basic runway | none | none |
| **NextGen 3** | comprehensive | basic runway | basic runway |
| **NextGen 4** | ground | ground | ground |

To evaluate safety in each NextGen environment, first, an ensemble of blunder encounters was generated and the number of collisions in the ensemble was determined. This number may be fractional because a probability was associated with each encounter. Then the ensemble was separated into 9 subgroups, one for each pair of aircraft classes. For each pair, the fraction of collisions prevented by situational awareness and by the alerting system was determined. Multiplying the number of collisions by the fraction of collisions remaining after SA and after alerting, the number of collisions was obtained for that class pair. Finally, the number of collisions in the ensemble with the benefits of SA and alerting was determined by summing over the class pairs. Comparing to the number of collisions without those benefits, the relative safety was determined. This procedure was performed for each NextGen environment, using the same ensemble for each.

Note that NextGen 1, the baseline, offered no SA or alerting benefits. Its relative collision risk was, by definition, 100%.

Tables 10 through Table 13 show these calculations in the four NextGen environments. The relative collision risks in each environment, highlighted in the lower right corner of each table, give the relative safety between the environments. Figure 22 plots this relative collision risk. It was found that NextGen 3 & 4 both feature a very low collision rate. The higher rate in NextGen 4 was due to the latency associated with transmitting measurements and alerts to and from the ground-based system. The NextGen 2 was much less safe than either NextGen 3 or 4, because some aircraft did not receive alerts and did not enjoy the same SA benefits. Still, NextGen 2 was much safer than the baseline, and NextGen 3 or 4 offer diminishing returns compared to the incremental benefit of NextGen 2.

**Table 10. Relative Collision Risk in NextGen1 Environment for Taxi Crossing Runway Scenario**

| Arriver Class | Taxier Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After SA | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 220.3 | N/A | N/A | 100.00% | 100.00% ± 0.00% |
| New | Retro | 224.5 | N/A | N/A | 100.00% | 100.00% ± 0.00% |
| New | Non | 41.4 | N/A | N/A | 100.00% | 100.00% ± 0.00% |
| Retro | New | 233.0 | N/A | N/A | 100.00% | 100.00% ± 0.00% |
| Retro | Retro | 192.3 | N/A | N/A | 100.00% | 100.00% ± 0.00% |
| Retro | Non | 31.4 | N/A | N/A | 100.00% | 100.00% ± 0.00% |
| Non | New | 32.9 | N/A | N/A | 100.00% | 100.00% ± 0.00% |
| Non | Retro | 45.8 | N/A | N/A | 100.00% | 100.00% ± 0.00% |
| Non | Non | 6.3 | N/A | N/A | 100.00% | 100.00% ± 0.00% |
| ***TOTAL*** | | ***1028.0*** | | | | ***100.00% ± 0.00%*** |

**Table 11. Relative Collision Risk in NextGen2 Environment for Taxi Crossing Runway Scenario**

| Arriver Class | Taxier Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | | | Relative Collision Risk After SA | Relative Collision Risk After Alerting & SA | | |
|---|---|---|---|---|---|---|---|---|---|---|
| New | New | 220.3 | both | 99.66% | ± | 0.29% | 8.00% | 0.03% | ± | 0.02% |
| New | Retro | 224.5 | arriver | 43.80% | ± | 3.45% | 32.00% | 17.98% | ± | 1.10% |
| New | Non | 41.4 | arriver | 35.47% | ± | 9.82% | 40.00% | 25.81% | ± | 3.93% |
| Retro | New | 233.0 | taxier | 99.97% | ± | 0.03% | 20.00% | 0.01% | ± | 0.01% |
| Retro | Retro | 192.3 | N/A | N/A | | | 80.00% | 80.00% | ± | 0.00% |
| Retro | Non | 31.4 | N/A | N/A | | | 100.00% | 100.00% | ± | 0.00% |
| Non | New | 32.9 | taxier | 100.00% | ± | 0.00% | 20.00% | 0.00% | ± | 0.00% |
| Non | Retro | 45.8 | N/A | N/A | | | 80.00% | 80.00% | ± | 0.00% |
| Non | Non | 6.3 | N/A | N/A | | | 100.00% | 100.00% | ± | 0.00% |
| ***TOTAL*** | | ***1028.0*** | | | | | | ***27.18%*** | ***±*** | ***0.29%*** |

**Table 12. Relative Collision Risk in NextGen3 Environment for Taxi Crossing Runway Scenario**

| Arriver Class | Taxier Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | | | Relative Collision Risk After SA | Relative Collision Risk After Alerting & SA | | |
|---|---|---|---|---|---|---|---|---|---|---|
| New | New | 220.3 | both | 99.66% | ± | 0.29% | 8.00% | 0.03% | ± | 0.02% |
| New | Retro | 224.5 | both | 99.97% | ± | 0.02% | 8.00% | 0.00% | ± | 0.00% |
| New | Non | 41.4 | both | 98.21% | ± | 1.19% | 8.00% | 0.14% | ± | 0.10% |
| Retro | New | 233.0 | both | 99.97% | ± | 0.03% | 8.00% | 0.00% | ± | 0.00% |
| Retro | Retro | 192.3 | both | 100.00% | ± | 0.00% | 8.00% | 0.00% | ± | 0.00% |
| Retro | Non | 31.4 | both | 100.00% | ± | 0.00% | 8.00% | 0.00% | ± | 0.00% |
| Non | New | 32.9 | both | 100.00% | ± | 0.00% | 8.00% | 0.00% | ± | 0.00% |
| Non | Retro | 45.8 | both | 100.00% | ± | 0.00% | 8.00% | 0.00% | ± | 0.00% |
| Non | Non | 6.3 | both | 100.00% | ± | 0.00% | 8.00% | 0.00% | ± | 0.00% |
| ***TOTAL*** | | ***1028.0*** | | | | | | ***0.01%*** | ***±*** | ***0.01%*** |

**Table 13. Relative Collision Risk in NextGen4 Environment for Taxi Crossing Runway Scenario**

| Arriver Class | Taxier Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After SA | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 220.3 | ground | 97.15% ± 0.95% | 8.00% | 0.23% ± 0.08% |
| New | Retro | 224.5 | ground | 96.37% ± 0.95% | 8.00% | 0.29% ± 0.08% |
| New | Non | 41.4 | ground | 96.98% ± 1.81% | 8.00% | 0.24% ± 0.14% |
| Retro | New | 233.0 | ground | 97.00% ± 1.10% | 8.00% | 0.24% ± 0.09% |
| Retro | Retro | 192.3 | ground | 98.04% ± 1.01% | 8.00% | 0.16% ± 0.08% |
| Retro | Non | 31.4 | ground | 95.35% ± 2.95% | 8.00% | 0.37% ± 0.24% |
| Non | New | 32.9 | ground | 99.72% ± 0.49% | 8.00% | 0.02% ± 0.04% |
| Non | Retro | 45.8 | ground | 100.00% ± 0.00% | 8.00% | 0.00% ± 0.00% |
| Non | Non | 6.3 | ground | 100.00% ± 0.00% | 8.00% | 0.00% ± 0.00% |
| ***TOTAL*** | | ***1028.0*** | | | | ***0.22% ± 0.04%*** |

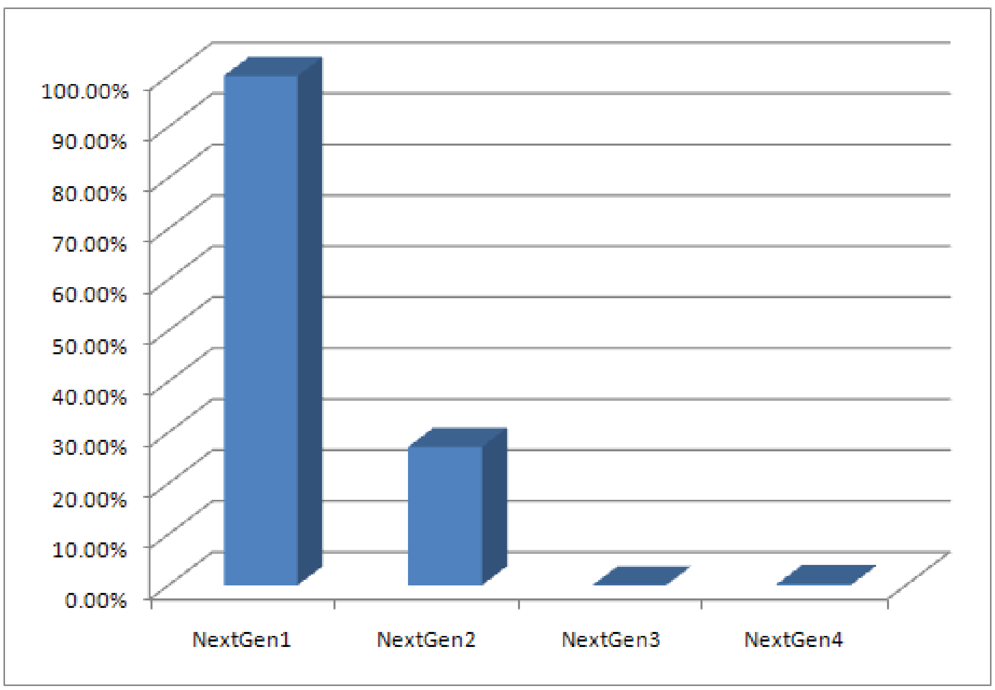



**Figure 22. Relative Collision Rates in Four NextGen Environments, Relative to the Baseline (NextGen1) for Taxi Crossing Runway Scenario**

### 6.2.8.1 Dependence on Fleet Composition

A fleet composition of 45% New Transport, 45% Retrofit Transport, and 10% Non-Transport was assumed. A variation was considered in which the composition was 30% New Transport, 50% Retrofit Transport, and 20% Non-Transport – overall a less-equipped mixture of aircraft. Table 14 shows the relative collision rate based on the effects of situational awareness and alerting in each NextGen environment for each fleet mixture. The older fleet increased the collision rate in the NextGen 2

environment, where Retrofit Transport and especially Non-Transport were relatively less equipped. Otherwise, there was little difference because equipage was similar among the other three classes.

**Table 14. Collision Rate Relative to Baseline in Each NextGen Environment as a Function of Fleet Composition for Runway Crossing Scenario**

| | Baseline Fleet | Older Fleet |
|---|---|---|
| **NextGen 1** | 100.0% | 100.0% |
| **NextGen 2** | 27.2% | 42.3 % |
| **NextGen 3** | 0.0% | 0.0% |
| **NextGen 4** | 0.2% | 0.2% |

## 6.3 Scenario 2: Intersecting Arrivals

### 6.3.1 Overview

Figure 23 shows a diagram of the scenario. Two arriving aircraft landed on intersecting runways. The intersection was located a variable distance (0 to 1000 meters) from each runway threshold (with a different distance for each runway). The angle between runways, taken to be 45 degrees, was relatively unimportant to the results.

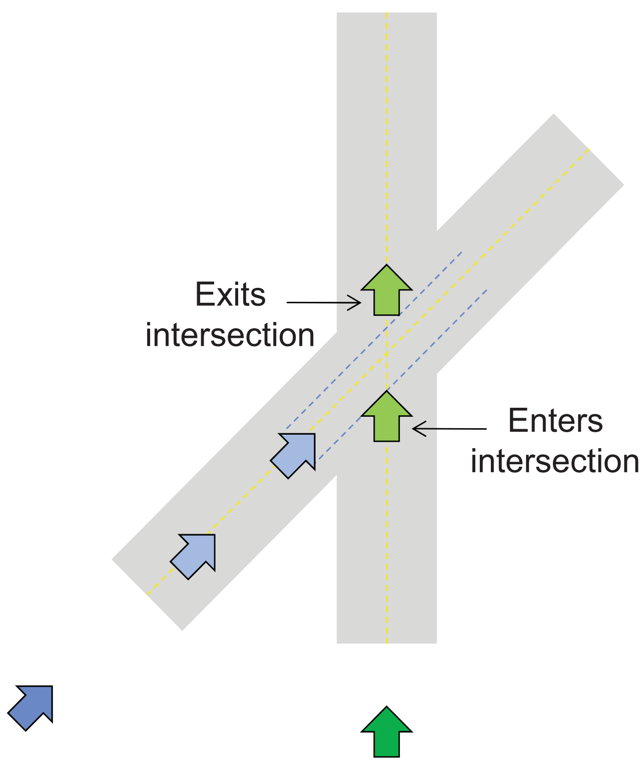



**Figure 23. Intersecting Arrivals Scenario**

### 6.3.2 Scenario Model

For each of the two arrivers, the same arriver model was used as in the taxi crossing runway scenario.

### 6.3.3 Collision Risk With and Without an Alert

Collision risk was modeled with the same function as in the taxi crossing runway scenario; it was based on the distance margin between the two aircraft at the intersection. Collision risk after an alert was issued

was modeled by assuming that the alert instructed the arriver to go around (if before threshold) or to halt (if after touchdown). Again, this matches the procedure used in the taxi crossing runway scenario.

### 6.3.4 Projected Times and Margins

Times were projected for when each aircraft would enter and leave the intersection, and the two safety margins were computed just as in the previous scenario. An analogue of the "rules margin" was not calculated, as there was no corresponding rule that must be followed (aside from anticipated separation).

### 6.3.5 Alerting Algorithm

The alerting algorithm was similar to the algorithm for the taxi crossing runway scenario. The same requirements on safety margin and arriver position were used. Alerts were generated only if both aircraft were less than 30 seconds from threshold and had not yet passed through the intersection. One significant difference was that there was no analogue to the "rules margin" requirement.

For on-board alerts, no coordination was assumed between the two aircraft; each aircraft chose whether to alert without knowledge of the other aircraft's decision (and without even knowing if the other aircraft had an alerting system). After both aircraft have touched down, both could be instructed to halt even if it would have been advantageous for one to proceed while the other halted. In most cases it was better for both to halt than for both to proceed without an alert.

A ground-based alerting system could choose to alert just one of the two aircraft if it believed that was the best response. In the system modeled, if an alert was to be issued and the two aircraft were predicted to enter the intersection within 3 seconds of each other, both received an alert. If both aircraft have touched down and one entered more than 3 seconds after the other, only the later aircraft received an alert. If one or both aircraft were still airborne and could be instructed to go around, both received an alert. It was assumed that the two aircraft were always successful in avoiding each other if both went around.

### 6.3.6 Nuisance Alert Rate

The nuisance alert rate was evaluated in an ensemble of encounters taken to represent normal operations. In this ensemble, it was assumed that the true safety margin between the two aircraft was 5 to 15 seconds. None of these encounters pose a collision risk.

An ensemble of 400,000 encounters was simulated with a ground-based alerting system. None of these encounters generated an alert. Based on a binomial distribution, this shows that the nuisance alert rate was less than $0.9 \times 10^{-5}$ at 95% confidence. Thus, it was validated that the nuisance alert rate was low for the ground-based alerting system. While this test was not been performed for on-board alerts, there is no reason to suspect a significant difference.

### 6.3.7 Alert Effectiveness

Figure 24 shows collision risk as a function of the true safety margin time between the two arrivals, with alerts issued to neither, one, or both aircraft. It was found that no collisions occurred when any alerting system was in place; alerts issued to one or both aircraft were very effective.

The reduction in collision risk came entirely from go-around alerts issued before threshold, rather than alerts issued after touchdown.

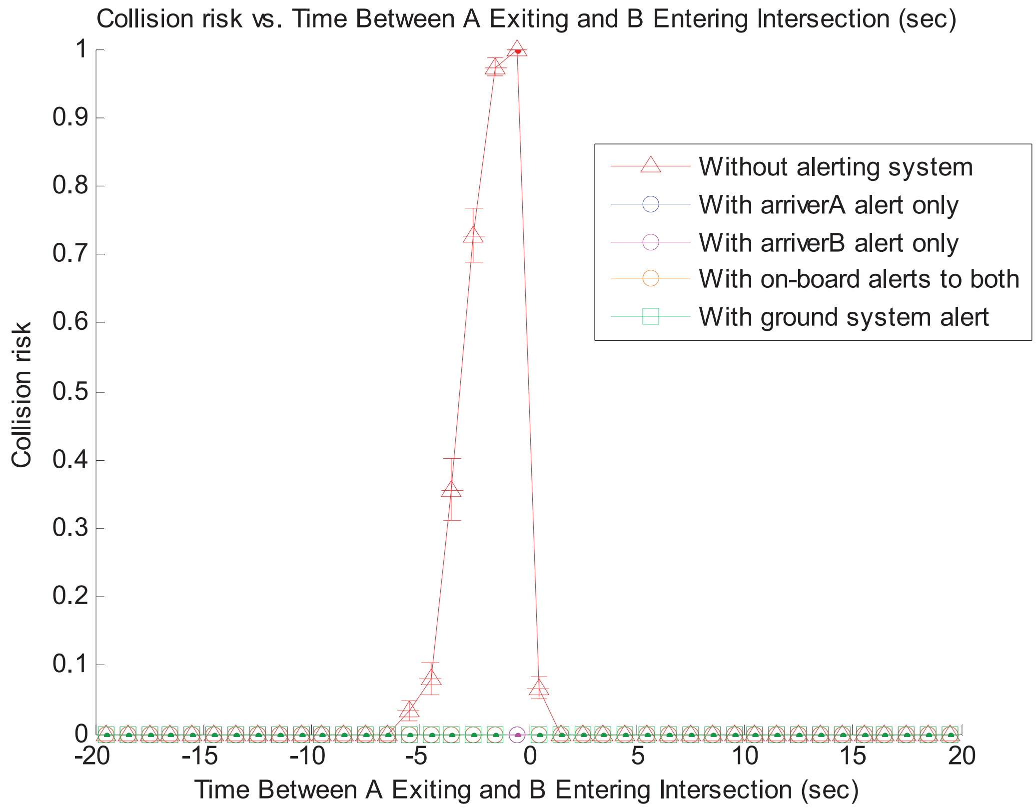



**Figure 24. Collision Risk as a Function of Safety Margin for Intersecting Arrivals Scenario**

#### 6.3.7.1 Dependence on Response time

As in the previous scenario, dependence on response time was evaluated by doubling and halving it. Table 15 shows the fraction of collisions averted as response time varied. It is shown that even when response times doubled, the alerting system was very effective. This is because alerts are typically issued long before the aircraft is at threshold.

**Table 15. Fraction of Collisions Averted by Alerting as a Function of Response time**

| | Response times x½ | Baseline | Response times x2 |
|---|---|---|---|
| **Arriver A Alert Only** | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 99.9 ± 0.1 % |
| **Arriver B Alert Only** | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 99.5 ± 0.2 % |
| **On-Board Alerts to Both** | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| **Ground-Based Alerts to Both** | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |

#### 6.3.7.2 Dependence on Position Measurement Precision

A one-sigma position measurement accuracy of 5 m was assumed. To explore the sensitivity of alert effectiveness to this parameter, new ensembles were generated with accuracies of 2.5 m and 10 m. Table 16 shows the fraction of collisions averted as measurement precision varied. The alerting system was always 100% effective, even at 10 m precision.

**Table 16. Fraction of Collisions Averted by Alerting as a Function of Position Measurement Precision**

| | 2.5m Precision | 5m Precision | 10m Precision |
|---|---|---|---|
| Arriver A Alert Only | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| Arriver B Alert Only | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| On-Board Alerts to Both | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| Ground-Based Alerts to Both | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |

#### 6.3.7.3 Dependence on ADS-B Velocity Measurement

The alerting algorithm was assumed to have access to an independent ADS-B measurement of velocity, rather than being limited to a velocity estimated from position measurements. The assumed accuracy of this measurement, either 0.03 m/s or 0.10 m/s according to the equipage model described in Section 6.1.3, was much better than the accuracy for velocity derived from smoothing recent position measurements. To explore the sensitivity of alert effectiveness to the availability of this measurement, alert effectiveness was evaluated with and without it. Table 17 shows the results. Alerting was always 100% effective in both cases, and so the high-precision ADS-B velocity measurement did not improve alert effectiveness.

As in the previous scenario, the alert rate did increase for encounters that were safe but were also close to a collision risk.

**Table 17. Fraction of Collisions Averted by Alerting with and without ADS-B Velocity Measurement**

| | With ADS-B Velocity | Without ADS-B Velocity |
|---|---|---|
| Arriver A Alert Only | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| Arriver B Alert Only | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| On-Board Alerts to Both | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| Ground-Based Alerts to Both | 100.0 ± 0.0 % | 100.0 ± 0.0 % |

### 6.3.8 Comparison of NextGen Environments

Safety was evaluated in the four NextGen environments using the same technique as in the taxi crossing runway scenario. For SA, it was assumed that CDTI enabled a pilot to avoid 60% of blunders. It was also assumed that non-traffic alerting offered no benefit in this scenario. Alerts were generated for all aircraft with comprehensive or basic runway alerting or for all aircraft if a ground-based system was present.

Tables 18 through Table 21 show the calculations and results. Figure 25 plots relative safety in the four environments. As in the taxi crossing runway scenario, NextGen 3 or 4 equipages eliminated almost all collisions, while NextGen 2 equipage eliminated a majority of collisions.

**Table 18. Relative Collision Risk in NextGen1 Environment for Intersecting Arrivals Scenario**

| Arriver A Class | Arriver B Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 82.7 | x | ± | 100.00% | 100.00% ± 0.00% |
| New | Retro | 77.0 | x | ± | 100.00% | 100.00% ± 0.00% |
| New | Non | 20.2 | x | ± | 100.00% | 100.00% ± 0.00% |
| Retro | New | 89.7 | x | ± | 100.00% | 100.00% ± 0.00% |
| Retro | Retro | 96.8 | x | ± | 100.00% | 100.00% ± 0.00% |
| Retro | Non | 13.4 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | New | 12.1 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | Retro | 17.3 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | Non | 2.0 | x | ± | 100.00% | 100.00% ± 0.00% |
| ***TOTAL*** | | ***411.2*** | | | | ***100.00% ± 0.00%*** |

**Table 19. Relative Collision Risk in NextGen2 Environment for Intersecting Arrivals Scenario**

| Arriver A Class | Arriver B Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 82.7 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| New | Retro | 77.0 | A | 100.00% ± 0.00% | 40.00% | 0.00% ± 0.00% |
| New | Non | 20.2 | A | 100.00% ± 0.00% | 40.00% | 0.00% ± 0.00% |
| Retro | New | 89.7 | B | 100.00% ± 0.00% | 40.00% | 0.00% ± 0.00% |
| Retro | Retro | 96.8 | x | ± | 100.00% | 100.00% ± 0.00% |
| Retro | Non | 13.4 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | New | 12.1 | B | 100.00% ± 0.00% | 40.00% | 0.00% ± 0.00% |
| Non | Retro | 17.3 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | Non | 2.0 | x | ± | 100.00% | 100.00% ± 0.00% |
| ***TOTAL*** | | ***411.2*** | | | | ***31.50% ± 0.00%*** |

**Table 20. Relative Collision Risk in NextGen3 Environment for Intersecting Arrivals Scenario**

| Arriver A Class | Arriver B Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 82.7 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| New | Retro | 77.0 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| New | Non | 20.2 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Retro | New | 89.7 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Retro | Retro | 96.8 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Retro | Non | 13.4 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Non | New | 12.1 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Non | Retro | 17.3 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Non | Non | 2.0 | both | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| ***TOTAL*** | | ***411.2*** | | | | ***0.00% ± 0.00%*** |

**Table 21. Relative Collision Risk in NextGen4 Environment for Intersecting Arrivals Scenario**

| Arriver A Class | Arriver B Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 82.7 | ground | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| New | Retro | 77.0 | ground | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| New | Non | 20.2 | ground | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Retro | New | 89.7 | ground | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Retro | Retro | 96.8 | ground | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Retro | Non | 13.4 | ground | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Non | New | 12.1 | ground | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Non | Retro | 17.3 | ground | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| Non | Non | 2.0 | ground | 100.00% ± 0.00% | 16.00% | 0.00% ± 0.00% |
| ***TOTAL*** | | ***411.2*** | | | | ***0.00% ± 0.00%*** |

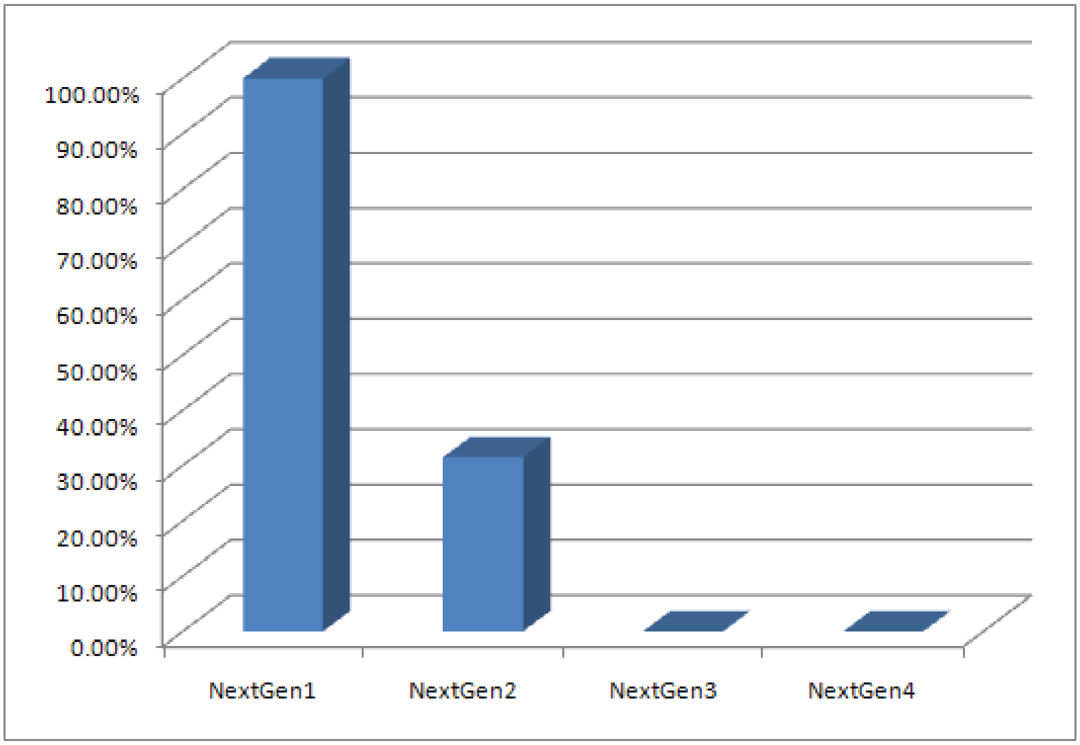



**Figure 25. Relative Collision Rates in Four NextGen Environments, Relative to the Baseline (NextGen1) for Intersecting Arrivals Scenario**

#### 6.3.8.1 Dependence on Fleet Composition

A fleet composition of 45% New Transport, 45% Retrofit Transport, and 10% Non-Transport was assumed. A variation was considered in which the composition is 30% New Transport, 50% Retrofit Transport, and 20% Non-Transport – overall a less-equipped mixture of aircraft. Table 22 shows the relative collision rate based on the effects of the combination of situational awareness and alerting in each NextGen environment for each fleet mixture. The older fleet increased the collision rate in the NextGen 2 environment, where Retrofit Transport and Non-Transport were relatively less equipped. Otherwise, there was little difference because equipage was similar among the other three classes.

**Table 22. Collision Rate Relative to Baseline in Each NextGen Environment as a Function of Fleet Composition for Intersecting Arrivals Scenario**

| | Baseline Fleet | Older Fleet |
|---|---|---|
| **NextGen 1** | 100.0% | 100.0% |
| **NextGen 2** | 31.5% | 49.1 % |
| **NextGen 3** | 0.0% | 0.0% |
| **NextGen 4** | 0.0% | 0.0% |

## 6.4 Scenario 3: Taxi Following

### 6.4.1 Overview

Figure 26 shows a diagram of the scenario. A lead aircraft taxied at constant speed (or stopped with zero speed) while a follower approached at a greater speed. At some distance the follower began to brake at a fixed deceleration. Braking continued until the follower matched speed with the arriver. At this point the aircraft moved together with a fixed separation distance between them.

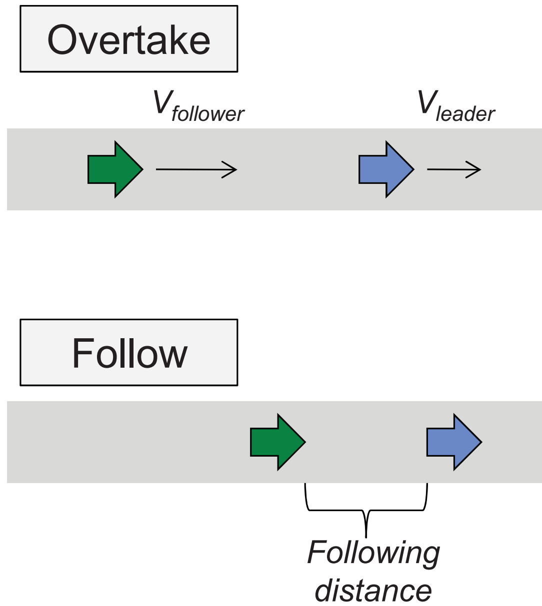



**Figure 26. Taxi Following Scenario**

### 6.4.2 Scenario Model

Aircraft movement was modeled along a straight line (or a fixed route). The leader maintained constant speed. The follower approached at constant speed, decelerated to match the leader's speed, and then continued at constant speed. Figure 27 shows the position and speed profiles of the two aircraft in an example encounter.

### 6.4.3 Collision Risk With and Without an Alert

Collision risk was defined as a function of the minimum separation between the follower's nose and the leader's tail. If this separation was safely positive, there was no collision risk. If it was negative, there was high collision risk. As in the previous scenarios, a transition between these regimes was also captured; here the function was a linear transition from zero collision risk at +5 m or greater to certainty of collision at -5 m or worse.

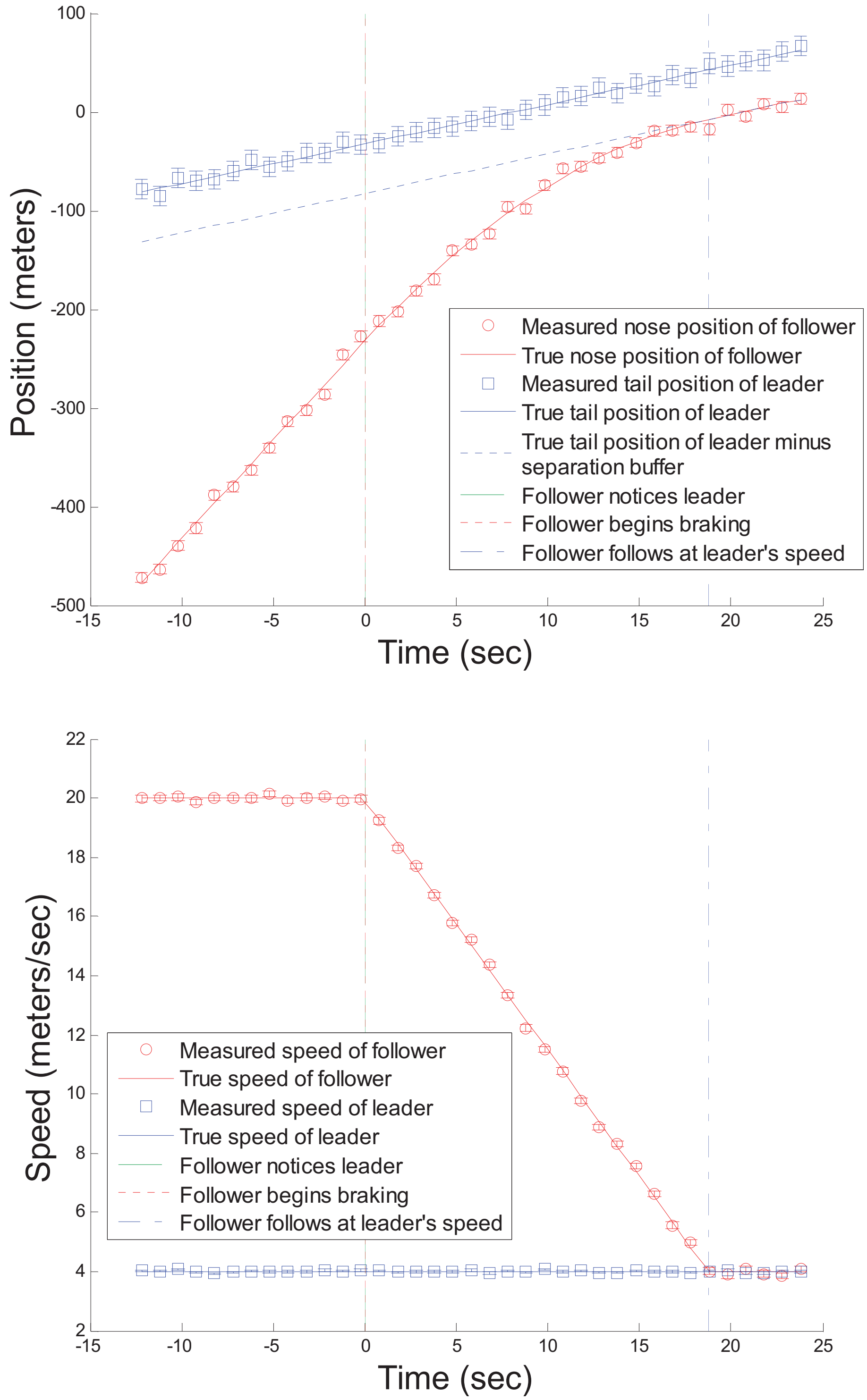



**Figure 27. Position and Speed of Aircraft in Taxi Following Scenario**

### 6.4.4 Projected Separation

The distance of closest point of approach was calculated if the follower initiated a comfortable braking deceleration (-1 m/s$^2$) at the current time. Figure 28 shows an example of this projected distance as a function of time (in this example, the true separation is 50 m). The deceleration assumed in this projection may not match the true braking deceleration; -1 m/s$^2$ is the strongest deceleration that an aircraft would choose if it did not have to stop urgently.

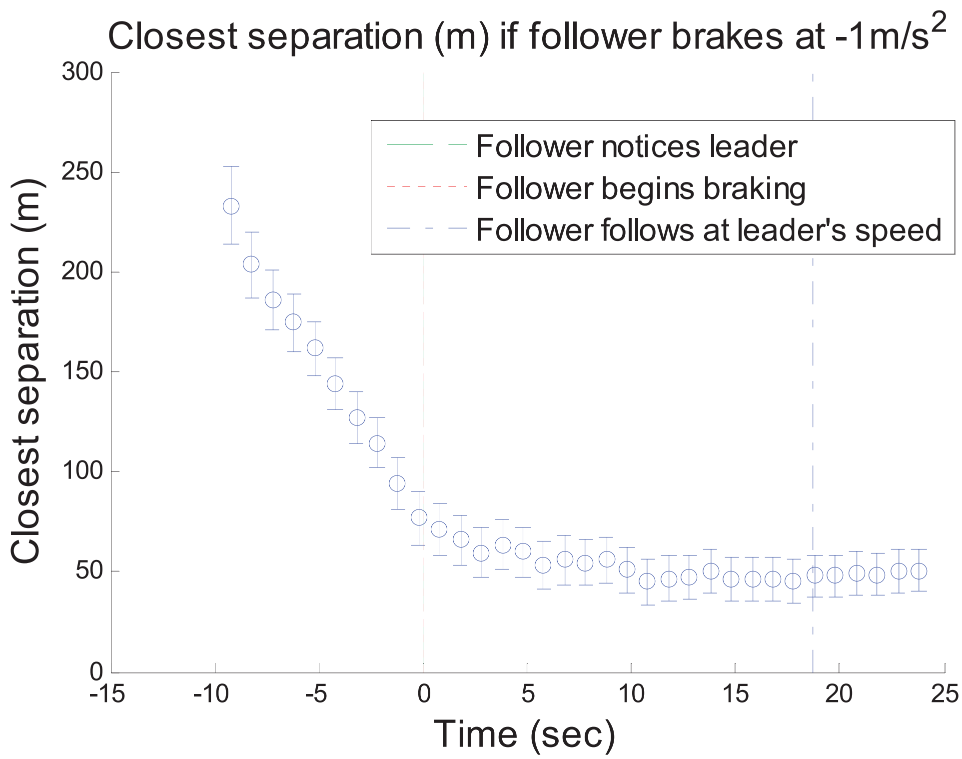



**Figure 28. Projected Minimum Separation as a Function of Time**

### 6.4.5 Alerting Algorithm

Alerts were issued only to the follower; an alert instructed the follower to brake. Alerts were not issued to the leader prescribing an increase in speed.

The alert variables were the current separation between aircraft and the distance of closest point of approach if the follower initiated a comfortable braking deceleration (-1 m/s$^2$) at the current time. If the current separation was less than 200 m and the distance of closest approach was smaller than a conventional distance between taxiing aircraft (50 m), an alert was issued. In fact it was required that the distance of closest point of approach was below 50 m by more than twice its uncertainty; this ensured that an alert was issued only when a violation of conventional separation was nearly certain. This criterion prevented nuisance alerts. No additional criterion was added requiring a significant collision risk, as violations of conventional separation usually present significant risk and are worthy of an alert.

### 6.4.6 Nuisance Alert Rate

The nuisance alert rate was evaluated in an ensemble of encounters taken to represent normal operations. In this ensemble, it was assumed that the follower noticed the leader at a distance no less than 200 m, and braked gently to match speed with no collision risk.

An ensemble of 400,000 encounters was simulated with a ground-based alerting system. None of these encounters generated an alert. Based on a binomial distribution, this shows that the nuisance alert rate

was less than 0.9 x $10^{-5}$ at 95% confidence. Thus, it is validated that the nuisance alert rate was acceptably low for the ground-based alerting system. While this test was not performed for on-board alerts, there is no reason to suspect a significant difference.

### 6.4.7 Alert Effectiveness

Collision risk in the absence of an alerting system depended strongly on the speed difference between aircraft and the distance between aircraft when the follower noticed the leader and began braking. Figure 29 and Figure 30 show the collision risk with and without alerting as a function of these variables. As expected, a large speed difference or small distance increased the collision risk. Alerting was effective, with greater effectiveness for on-board alerting due to the reduced latency.

Alert effectiveness depended strongly on pilot response time. Figure 31 shows collision risk as a function of response time, derived empirically from the Monte Carlo trials. Without an alerting system, the collision risk was insensitive to response time, as expected. However, with an alert the collision risk increased rapidly with response time up to approximately 6 seconds reaction time. The small number of cases with a larger reaction time made the success ratio an unreliable indicator beyond this point.

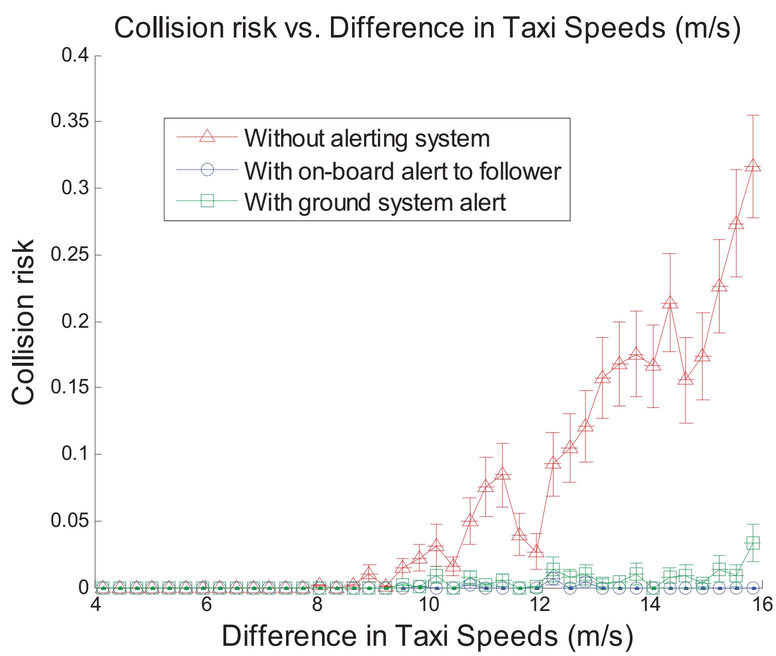



**Figure 29. Collision Risk vs. Speed Difference for Taxi Following Scenario**

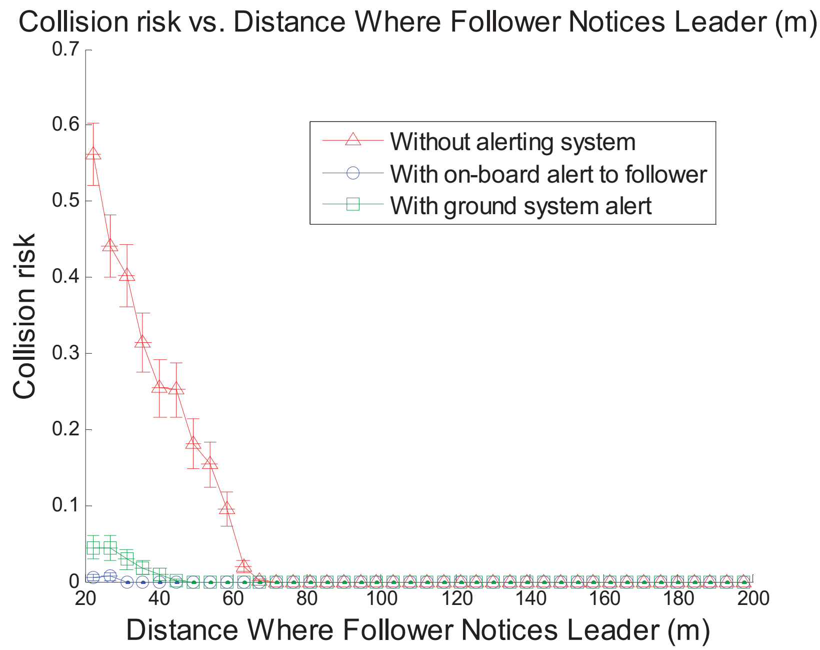



**Figure 30. Collision Risk vs. Braking Initiation Distance for Taxi Following Scenario**

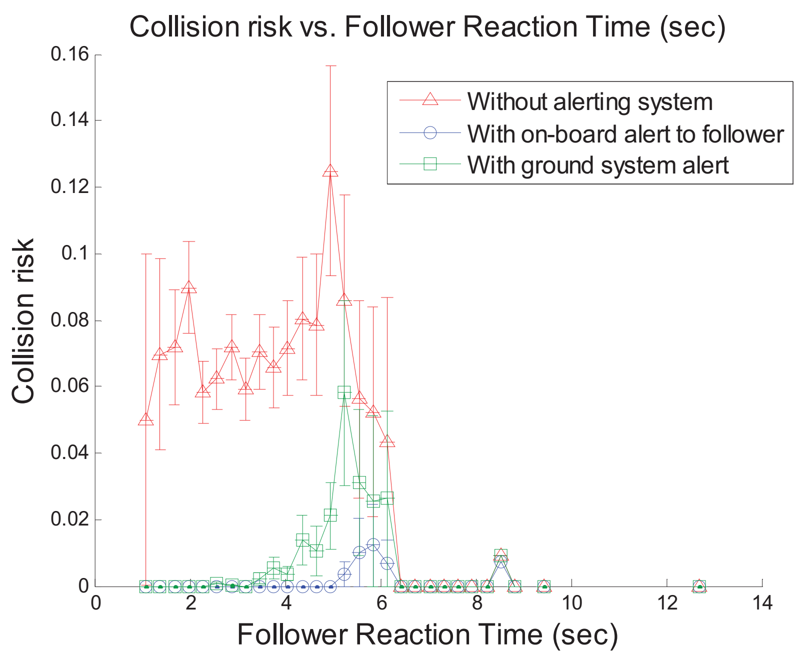



**Figure 31. Collision Risk vs. Follower Response Time for Taxi Following Scenario**

#### 6.4.7.1 Dependence on Response time

As in the previous scenarios, dependence on response time was evaluated by doubling and halving it. Table 23 shows the fraction of collisions averted as response time varied. It is shown that alert effectiveness was very sensitive to increased response time. The reduced effectiveness of ground-based alerts, relative to on-board, was due to the additional latency in the ground-based system.

**Table 23. Fraction of Collisions Averted by Alerting as a Function of Response time**

| | Response times x½ | Baseline | Response times x2 |
|---|---|---|---|
| **On-board Alert** | 100.0 ± 0.0 % | 99.1 ± 0.3 % | 67.2 ± 0.9 % |
| **Ground-Based Alert** | 100.0 ± 0.0 % | 93.6 ± 1.1 % | 42.7 ± 0.7 % |

#### 6.4.7.2 Dependence on Position Measurement Precision

A one-sigma position measurement accuracy of 5 m was assumed. To explore the sensitivity of alert effectiveness to this parameter, new ensembles were generated with accuracies of 2.5 m and 10 m. Table 24 shows the fraction of collisions averted as measurement precision varied. Modest improvement was seen in alert effectiveness as measurement precision improved.

**Table 24. Fraction of Collisions Averted by Alerting as a Function of Position Measurement Precision**

| | 2.5m Precision | 5m Precision | 10m Precision |
|---|---|---|---|
| **On-board Alert** | 99.2 ± 0.4 % | 98.7 ± 0.4 % | 96.9 ± 0.7 % |
| **Ground-Based Alert** | 95.7 ± 1.0 % | 92.5 ± 1.0 % | 91.5 ± 0.9 % |

#### 6.4.7.3 Dependence on ADS-B Velocity Measurement

The alerting algorithm was assumed to have access to an independent ADS-B measurement of velocity, rather than being limited to a velocity estimated from position measurements. The assumed accuracy of this measurement, either 0.03 m/s or 0.10 m/s according to the equipage model described in Section 6.1.3, was much better than the accuracy for velocity derived from smoothing recent position measurements. To explore the sensitivity of alert effectiveness to the availability of this measurement, alert effectiveness was evaluated with and without it. Table 25 shows the results. The alerting algorithm benefitted significantly from the high-precision ADS-B velocity measurement, especially for a ground-based alert system.

**Table 25. Fraction of Collisions Averted by Alerting with and without ADS-B Velocity Measurement**

| | With ADS-B Velocity | Without ADS-B Velocity |
|---|---|---|
| **On-board Alert** | 99.7 ± 0.3 % | 87.7 ± 1.8 % |
| **Ground-Based Alert** | 96.3 ± 1.0 % | 46.5 ± 2.1 % |

### 6.4.8 Comparison of NextGen Environments

Safety was evaluated for the four NextGen environments using the same technique as in the previous scenarios. For situational awareness, it was assumed that CDTI enabled a pilot to avoid 80% of blunders. It was also assumed that non-traffic alerting offered no benefit in this scenario. Alerts were generated for all aircraft with comprehensive alerting (but not basic runway alerting), or for all aircraft if a ground-based system was present.

Tables 26 through Table 29 show the calculations and results. Figure 32 plots relative collision risk in the four environments.

**Table 26. Relative Collision Risk in NextGen1 Environment for Taxi Following Scenario**

| Follower Class | Leader Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 68.3 | x | ± | 100.00% | 100.00% ± 0.00% |
| New | Retro | 72.4 | x | ± | 100.00% | 100.00% ± 0.00% |
| New | Non | 12.9 | x | ± | 100.00% | 100.00% ± 0.00% |
| Retro | New | 70.2 | x | ± | 100.00% | 100.00% ± 0.00% |
| Retro | Retro | 67.3 | x | ± | 100.00% | 100.00% ± 0.00% |
| Retro | Non | 17.4 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | New | 20.6 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | Retro | 12.7 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | Non | 2.0 | x | ± | 100.00% | 100.00% ± 0.00% |
| ***TOTAL*** | | ***343.7*** | | | | ***100.00% ± 0.00%*** |

**Table 27. Relative Collision Risk in NextGen2 Environment for Taxi Following Scenario**

| Follower Class | Leader Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 68.3 | x | ± | 20.00% | 20.00% ± 0.00% |
| New | Retro | 72.4 | x | ± | 20.00% | 20.00% ± 0.00% |
| New | Non | 12.9 | x | ± | 20.00% | 20.00% ± 0.00% |
| Retro | New | 70.2 | x | ± | 100.00% | 100.00% ± 0.00% |
| Retro | Retro | 67.3 | x | ± | 100.00% | 100.00% ± 0.00% |
| Retro | Non | 17.4 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | New | 20.6 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | Retro | 12.7 | x | ± | 100.00% | 100.00% ± 0.00% |
| Non | Non | 2.0 | x | ± | 100.00% | 100.00% ± 0.00% |
| ***TOTAL*** | | ***343.7*** | | | | ***64.26% ± 0.00%*** |

**Table 28. Relative Collision Risk in NextGen3 Environment for Taxi Following Scenario**

| Follower Class | Leader Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 68.3 | follower | 99.76% ± 0.31% | 20.00% | 0.05% ± 0.06% |
| New | Retro | 72.4 | follower | 99.00% ± 0.64% | 20.00% | 0.20% ± 0.13% |
| New | Non | 12.9 | follower | 95.43% ± 2.84% | 20.00% | 0.91% ± 0.57% |
| Retro | New | 70.2 | x | 0.00% ± 0.00% | 20.00% | 20.00% ± 0.00% |
| Retro | Retro | 67.3 | x | ± | 20.00% | 20.00% ± 0.00% |
| Retro | Non | 17.4 | x | ± | 20.00% | 20.00% ± 0.00% |
| Non | New | 20.6 | x | 0.00% ± 0.00% | 20.00% | 20.00% ± 0.00% |
| Non | Retro | 12.7 | x | ± | 20.00% | 20.00% ± 0.00% |
| Non | Non | 2.0 | x | ± | 20.00% | 20.00% ± 0.00% |
| ***TOTAL*** | | ***343.7*** | | | | ***11.15% ± 0.04%*** |

**Table 29. Relative Collision Risk in NextGen4 Environment for Taxi Following Scenario**

| Follower Class | Leader Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA |
|---|---|---|---|---|---|---|
| New | New | 68.3 | ground | 96.37% ± 2.99% | 20.00% | 0.73% ± 0.60% |
| New | Retro | 72.4 | ground | 93.91% ± 2.42% | 20.00% | 1.22% ± 0.48% |
| New | Non | 12.9 | ground | 91.61% ± 4.53% | 20.00% | 1.68% ± 0.91% |
| Retro | New | 70.2 | ground | 93.78% ± 2.50% | 20.00% | 1.24% ± 0.50% |
| Retro | Retro | 67.3 | ground | 96.65% ± 2.32% | 20.00% | 0.67% ± 0.46% |
| Retro | Non | 17.4 | ground | 94.05% ± 4.62% | 20.00% | 1.19% ± 0.92% |
| Non | New | 20.6 | ground | 90.09% ± 4.10% | 20.00% | 1.98% ± 0.82% |
| Non | Retro | 12.7 | ground | 96.99% ± 2.49% | 20.00% | 0.60% ± 0.50% |
| Non | Non | 2.0 | ground | 50.00% ± 50.00% | 20.00% | 10.00% ± 10.00% |
| ***TOTAL*** | | ***343.7*** | | | | ***1.11% ± 0.23%*** |

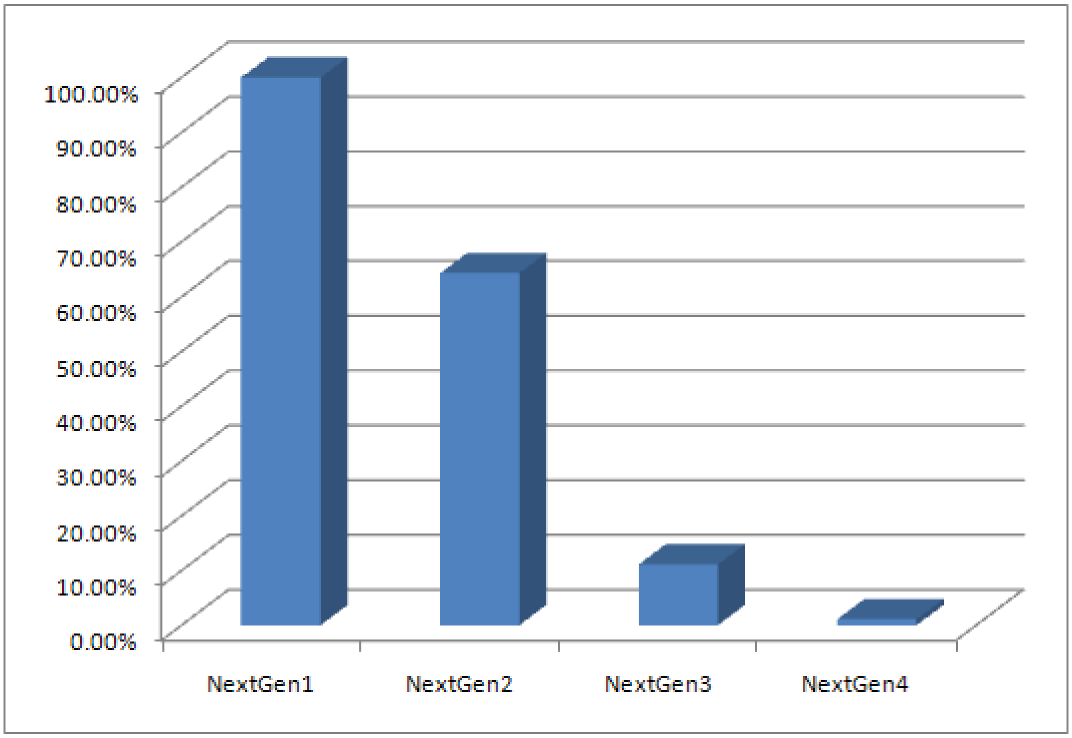



**Figure 32. Relative Collision Rates in Four NextGen Environments Relative to the Baseline (NextGen1) for Taxi Following Scenario**

#### 6.4.8.1 Dependence on Fleet Composition

A fleet composition of 45% New Transport, 45% Retrofit Transport, and 10% Non-Transport was assumed. A variation was considered in which the composition is 30% New Transport, 50% Retrofit Transport, and 20% Non-Transport—overall a less-equipped mixture of aircraft. Table 30 shows the relative collision rate based on the effects of the combination of situational awareness and alerting in each NextGen environment for each fleet mixture. The older fleet increased the collision rate in the NextGen 2 and NextGen 3 environments, where Retrofit Transport and Non-Transport were relatively less equipped. In NextGen 1 and 4, there was little difference because equipage was similar among both classes.

**Table 30. Collision Rate Relative to Baseline in Each NextGen Environment as a Function of Fleet Composition for Taxi Following Scenario**

| | Baseline Fleet | Older Fleet |
|---|---|---|
| **NextGen 1** | 100.0% | 100.0% |
| **NextGen 2** | 64.3% | 76.1 % |
| **NextGen 3** | 11.2% | 14.1% |
| **NextGen 4** | 1.1% | 1.3% |

## 6.5 Scenario 4: Arriver Following Lander

### 6.5.1 Overview

Figure 33 shows a diagram of the scenario. An arriver approached the runway as the previous aircraft, referred to as the "lander," was on the runway. There were two exits from the runway that were relevant. The expectation of the arriver, and the controller who issued clearance, was that the lander would leave the runway at the first exit with time to spare between its tail clearing the hold line and the arriver's nose crossing threshold. The lander decelerated with the intention of using the first exit, but at the last moment decided to take the second exit instead. As a result, the lander taxied along the runway at relatively low speed and then took the second exit. The lander therefore failed to clear the runway before the arriver crossed threshold, and there could have been a risk of collision.

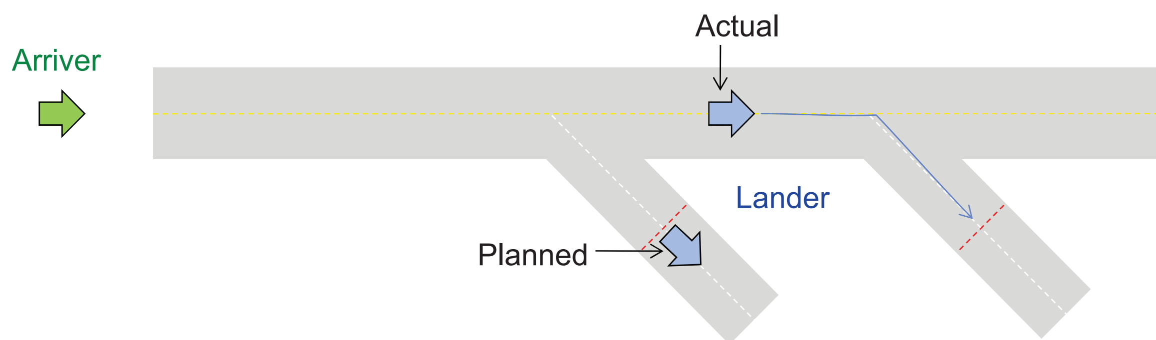



**Figure 33. Arriver Following Lander Scenario**

### 6.5.2 Scenario Model

For both aircraft, the same arriver model was used as in the previous scenarios. After landing, the arriver braked just as in the other scenarios. The lander braked in order to reach the rollout speed when its nose reached the center of the first intersection. If it had taken the first exit with this rollout speed, it would have cleared the hold line with some positive time margin before the arriver's nose crossed threshold. However, the lander instead proceeded at the rollout speed to the second exit, turned, and preceded off the runway with the same speed. Figure 34 shows the position and speed of the two aircraft as a function of time in a representative encounter. In this example, the arriver landed while the lander was still on the runway, but the two aircraft did not come close enough to collide.

### 6.5.3 Collision Risk with and without an Alert

Collision risk was modeled with the same function as in the taxi following scenario. This function was based on the distance of closest approach between the lander's tail and the arriver's nose, while both were on the runway. Collision risk after an alert was issued was modeled by assuming that the alert instructed the arriver to go around (if before threshold) or to halt (if after touchdown). This matched the procedure in the taxi crossing runway scenario. If an alert was issued to the lander, the lander increased speed to exit the runway earlier; collision risk was measured using the same function based on distance of closest approach.

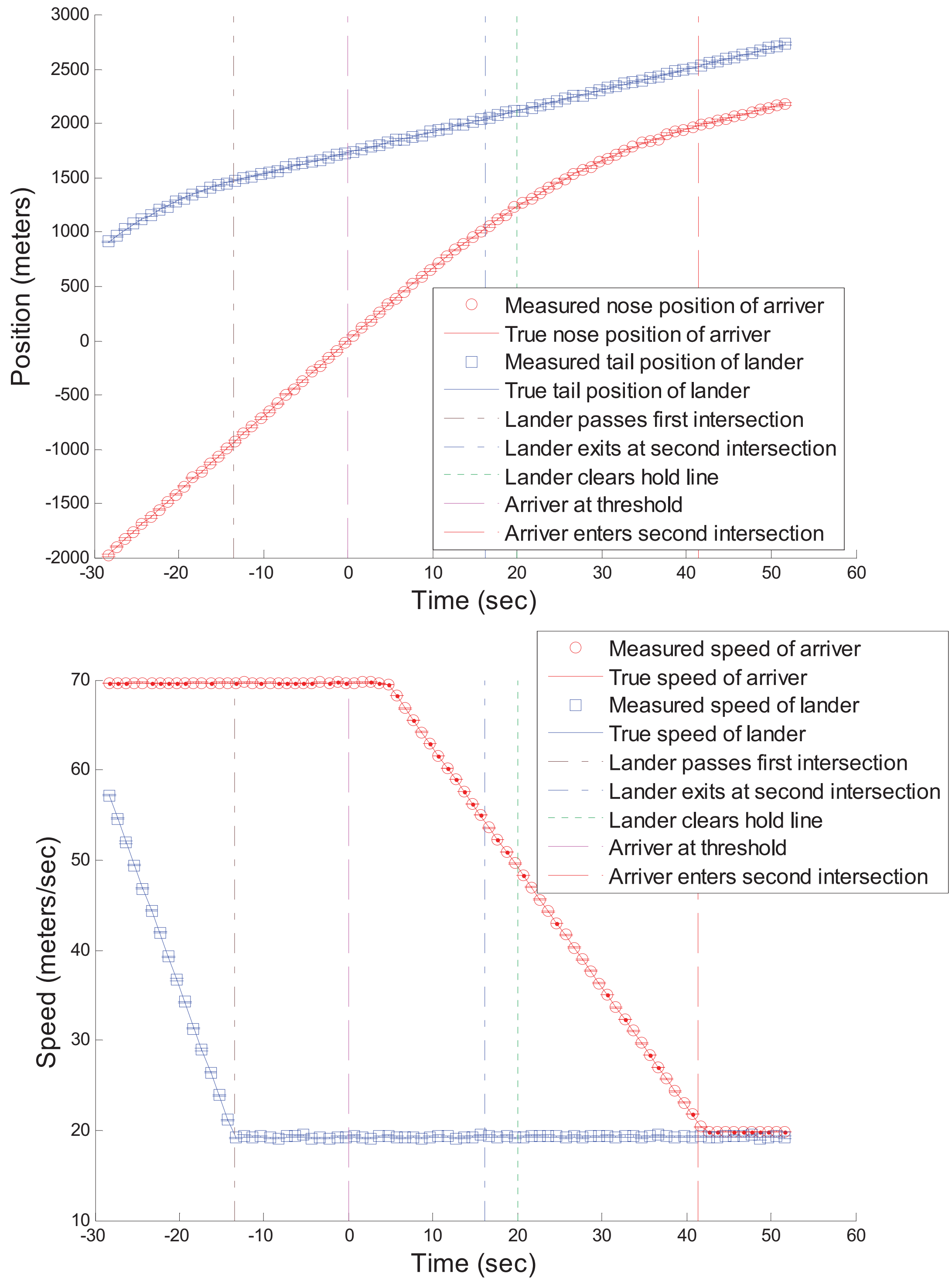



**Figure 34. Position (Top) and Speed (Bottom) of the Two Aircraft in the Arriver Following Lander Scenario**

### 6.5.4 Projected Times and Margins

The times when each aircraft would cross various points were projected. For the lander, when it would exit the second intersection and when it would clear the hold line were projected. For the arriver, when it would cross threshold and when it would enter the second intersection were projected. The difference between intersection exit and entry times was the safety margin, and the difference between hold line clearance and threshold crossing was the rules margin. Note that, in contrast with the taxi crossing runway and intersecting arrivals scenarios, there was only one conceivable hypothesis about which aircraft was in the intersection first, and so the safety margin only tested the difference between arriver entry time and lander exit time.

### 6.5.5 Alerting Algorithm

The alerting algorithm was similar to the algorithm for the taxi crossing runway and intersecting arrivals scenarios. The same requirements on safety margin and rules margin were used. As in the other scenarios, alerts were not issued when the arriver was more than 30 seconds from threshold.

The most significant change in this scenario was that alerts could not be issued before confidence was established that the lander had passed the first intersection. Without this requirement, there would have been many nuisance alerts issued in encounters where the lander was going to exit at the first intersection. In order to issue an alert, it was required that the lander's nose had passed beyond the center of the first intersection by a distance of 50 meters plus twice the position measurement uncertainty. This requirement was the most significant in the alerting process. After it was determined that the lander did not exit at the first intersection, it was very clear that a rules violation had occurred, and if there were significant collision risk that would also be very clear.

As a result, the performance of the alerting system, and the amount of warning time it gave, could be understood by analyzing the requirement on lander position. The plan was for the lander to exit at the first intersection's hold line with some amount of time to spare before the arriver crossed threshold. The lander was at the first intersection some time before the planned clearance time – the difference was the time required to travel from intersection to hold line at the rollout speed. When it instead proceeded along the runway, an alert was issued at a later time when it had traveled 50 meters plus twice the position measurement uncertainty. Therefore the expectation for the time when the alert was issued was:

$$T_{alert} = T_{thres} – ( \Delta t_{planned} + (d_{hold} + L_{ac} – 50m – 2*\delta p)/v_{rollout} )$$

Here, $T_{thres}$ was the time when the arriver crossed threshold, $\Delta t_{planned}$ was the planned time between that event and the lander clearing at the first exit, $d_{hold}$ was the distance between the center of the first intersection and the exit hold line, $L_{ac}$ was the aircraft length, $\delta p$ was the position measurement uncertainty, and $v_{rollout}$ was the speed of the lander after it reached the first intersection. Using typical parameter values $\Delta t_{planned}$ = 5 sec, $d_{hold}$ = 120 m (relatively long due to an assumed 45 degree angle between runway and exit), $L_{ac}$ = 40 m, $\delta p$ = 5 m, and v_rollout = 20 m/s, an alert was typically issued about 10 seconds before the arriver crossed threshold. Unless pilot response time was very long, this was typically enough time for the arriver to execute a go-around. Even if the arriver could not go around, it could brake harder on the runway to prevent a collision. Also, the taxier could speed up to exit the runway sooner. From this analysis, it was expected that the alert system would be very effective in preventing collisions.

### 6.5.6 Nuisance Alert Rate

The nuisance alert rate in an ensemble of encounters taken to represent normal operations was evaluated. This ensemble was identical to the blunder ensemble, except the lander exited at the first intersection (as the arriver expected). It was assumed that the alerting system determined that the lander was turning off when its nose was at a position near the center of the first intersection. The deviation from the center was randomly drawn from a Gaussian distribution with standard deviation of 15 m, but truncated at 30 m.

An ensemble of 400,000 encounters with a ground-based alerting system was simulated. None of these encounters generate an alert. Based on a binomial distribution, this shows that the nuisance alert rate was less than $0.9 \times 10^{-5}$ at 95% confidence. Thus it was validated that the nuisance alert rate was low for the ground-based alerting system. While this test was not performed for on-board alerts, there is no reason to suspect a significant difference.

### 6.5.7 Alert Effectiveness

Figure 35 shows collision risk as a function of the distances to the two runway exits, with alerts issued to neither, one, or both aircraft.

It is a general feature of this scenario that collisions are rare even if a blunder occurred and no alerting system was present, because the two aircraft started far from each other and moved in the same direction. A collision occurred only if all of the scenario parameters were unfavorable. For example, it can be seen in the figure that collisions occurred only when the first exit was close to threshold and the second intersection was far from the first.

Very few collisions occurred when an alerting system was in place; alerts issued to one or both aircraft were very effective. When the arriver received an alert, it usually went around, but even if that failed it could brake harder on the runway to avoid the lander. When the lander received an alert, it increased speed and exited the runway sooner.

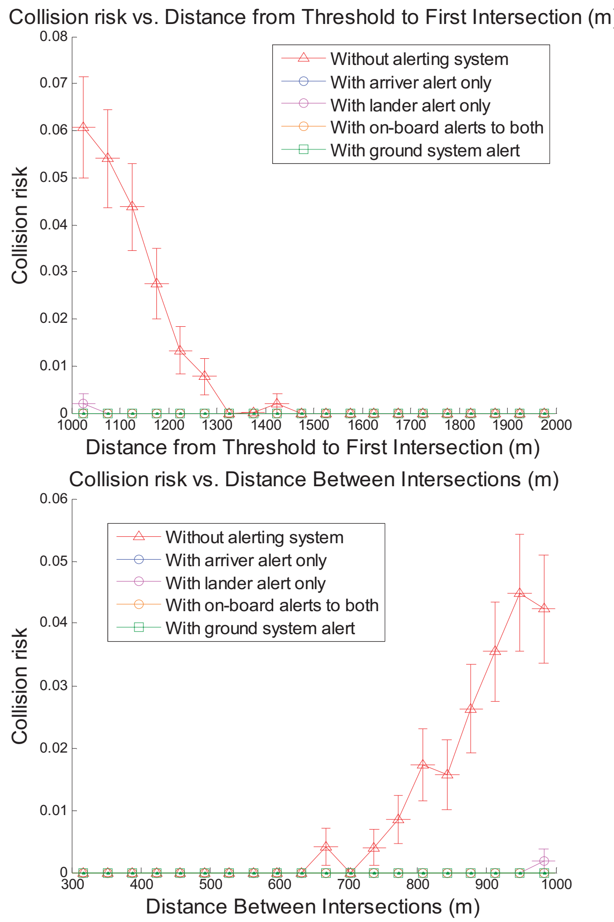



**Figure 35. Collision Risk as a Function of Distance to First Intersection (left) and Distance between Intersections (right) for Arriver Following Lander Scenario**

#### 6.5.7.1 Dependence on Response time

As in the previous scenarios, dependence on response time was evaluated by doubling and halving it. Table 31 shows the fraction of collisions averted as response time varied. It can be seen that alerting was very effective even if response times were doubled; this scenario was insensitive to pilot response time.

**Table 31. Fraction of Collisions Averted by Alerting as a Function of Response time**

| | Response times x1/2 | Baseline | Response times x2 |
|---|---|---|---|
| **Arriver Alert Only** | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| **Lander Alert Only** | 99.0 ± 0.8 % | 99.0 ± 0.8 % | 99.0 ± 0.8 % |
| **Ground-Based Alerts to Both** | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |

#### 6.5.7.2 Dependence on Position Measurement Precision

A position measurement precision of 5m was assumed. To explore the sensitivity of alert effectiveness to this parameter, new ensembles with precisions of 2.5m and 10m were generated. Table 32 shows the fraction of collisions averted as measurement precision varies. It can be seen that the alerting system was always very effective, even at 10m precision.

**Table 32. Fraction of Collisions Averted by Alerting as a Function of Position Measurement Precision**

| | 2.5m Precision | 5m Precision | 10m Precision |
|---|---|---|---|
| **Arriver Alert Only** | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| **Lander Alert Only** | 98.6 ± 1.3 % | 98.6 ± 1.3 % | 98.6 ± 1.3 % |
| **Ground-Based Alerts to Both** | 100.0 ± 0.0 % | 100.0 ± 0.0 % | 100.0 ± 0.0 % |

#### 6.5.7.3 Dependence on ADS-B Velocity Measurement

The alerting algorithm was assumed to have access to an independent ADS-B measurement of velocity, rather than being limited to a velocity estimated from position measurements. The assumed accuracy of this measurement, either 0.03 m/s or 0.10 m/s according to the equipage model described in Section 6.1.3, was much better than the accuracy for velocity derived from smoothing recent position measurements. To explore the sensitivity of alert effectiveness to the availability of this measurement, alert effectiveness was evaluated with and without it. Table 33 shows the results. Alerting was always very effective in both cases, and so the high-precision ADS-B velocity measurement did not improve alert effectiveness.

As in the previous scenarios, the alert rate did increase for encounters that were safe but contained a rules violation. In this scenario approximately 20% of such encounters produced an alert when the ADS-B velocity measurement was available, but without that measurement 80% of these encounters produced an alert. Such alerts are not considered nuisance alerts; they occur in cases where the arriver passed the threshold while the lander was still on the runway.

**Table 33. Fraction of Collisions Averted by Alerting with and without ADS-B Velocity Measurement**

| | With ADS-B Velocity | Without ADS-B Velocity |
|---|---|---|
| **Arriver Alert Only** | 100.0 ± 0.0 % | 100.0 ± 0.0 % |
| **Lander Alert Only** | 98.6 ± 1.3 % | 98.6 ± 1.3 % |
| **Ground-Based Alerts to Both** | 100.0 ± 0.0 % | 100.0 ± 0.0 % |

### 6.5.8 Comparison of NextGen Environments

Safety in the four NextGen environments was evaluated using the same technique as in the previous scenarios. For situational awareness, it was assumed that CDTI enabled the pilot of either aircraft to avoid 60% of blunder-induced collisions; either the lander cleared at the first exit as planned, the lander moved faster to the second exit, the arriver went around, or the arriver braked harder. It was assumed that non-traffic alerting allowed the lander to better know its position along the runway and relative to the exits, and this technology was credited with preventing 20% of blunders. Alerts were generated for all aircraft with comprehensive or basic runway alerting or for all aircraft if a ground-based system was present.

Tables 34 through Table 37 show the calculations and results. Figure 36 plots relative safety in the four environments. As in the taxi crossing runway and intersecting arrivals scenarios, NextGen 3 or 4 equipages eliminated almost all collisions, while NextGen 2 equipage eliminated a majority of collisions.

**Table 34. Relative Collision Risk in NextGen1 Environment for Arrival Following Lander Scenario**

| Arriver A Class | Arriver B Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | | | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA | | |
|---|---|---|---|---|---|---|---|---|---|---|
| New | New | 20.2 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| New | Retro | 21.3 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| New | Non | 6.0 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| Retro | New | 17.9 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| Retro | Retro | 16.7 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| Retro | Non | 4.0 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| Non | New | 6.1 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| Non | Retro | 8.0 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| Non | Non | 1.0 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| ***TOTAL*** | | ***101.1*** | | | | | | ***100.00%*** | ***±*** | ***0.00%*** |

**Table 35. Relative Collision Risk in NextGen2 Environment for Arrival Following Lander Scenario**

| Arriver A Class | Arriver B Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | | | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA | | |
|---|---|---|---|---|---|---|---|---|---|---|
| New | New | 20.2 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| New | Retro | 21.3 | arriver | 100.00% | ± | 0.00% | 32.00% | 0.00% | ± | 0.00% |
| New | Non | 6.0 | arriver | 100.00% | ± | 0.00% | 40.00% | 0.00% | ± | 0.00% |
| Retro | New | 17.9 | lander | 100.00% | ± | 0.00% | 40.00% | 0.00% | ± | 0.00% |
| Retro | Retro | 16.7 | x | | ± | | 80.00% | 80.00% | ± | 0.00% |
| Retro | Non | 4.0 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| Non | New | 6.1 | lander | 100.00% | ± | 0.00% | 40.00% | 0.00% | ± | 0.00% |
| Non | Retro | 8.0 | x | | ± | | 80.00% | 80.00% | ± | 0.00% |
| Non | Non | 1.0 | x | | ± | | 100.00% | 100.00% | ± | 0.00% |
| ***TOTAL*** | | ***101.1*** | | | | | | ***24.46%*** | ***±*** | ***0.00%*** |

**Table 36. Relative Collision Risk in NextGen3 Environment for Arrival Following Lander Scenario**

| Arriver A Class | Arriver B Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | | | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA | | |
|---|---|---|---|---|---|---|---|---|---|---|
| New | New | 20.2 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| New | Retro | 21.3 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| New | Non | 6.0 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Retro | New | 17.9 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Retro | Retro | 16.7 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Retro | Non | 4.0 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Non | New | 6.1 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Non | Retro | 8.0 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Non | Non | 1.0 | both | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| ***TOTAL*** | | ***101.1*** | | | | | | ***0.00%*** | ***±*** | ***0.00%*** |

**Table 37. Relative Collision Risk in NextGen4 Environment for Arrival Following Lander Scenario**

| Arriver A Class | Arriver B Class | # Collisions in Baseline | Alerting type | Fraction Averted by Alerting | | | Relative Collision Risk After Situational Awareness | Relative Collision Risk After Alerting & SA | | |
|---|---|---|---|---|---|---|---|---|---|---|
| New | New | 20.2 | ground | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| New | Retro | 21.3 | ground | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| New | Non | 6.0 | ground | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Retro | New | 17.9 | ground | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Retro | Retro | 16.7 | ground | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Retro | Non | 4.0 | ground | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Non | New | 6.1 | ground | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Non | Retro | 8.0 | ground | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| Non | Non | 1.0 | ground | 100.00% | ± | 0.00% | 16.00% | 0.00% | ± | 0.00% |
| ***TOTAL*** | | ***101.1*** | | | | | | ***0.00%*** | ***±*** | ***0.00%*** |

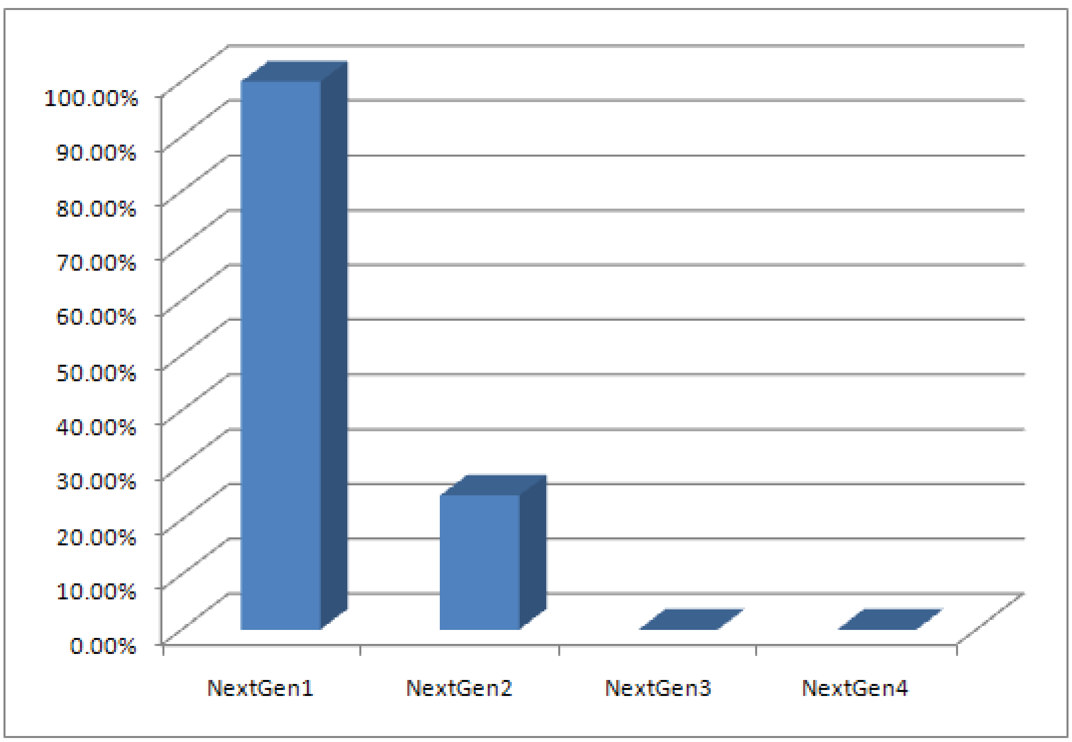



**Figure 36. Relative Collision Rates in Four NextGen Environments, Relative to the Baseline (NextGen1) for Arrival Following Lander Scenario**

#### 6.5.8.1 Dependence on Fleet Composition

A fleet composition of 45% New Transport, 45% Retrofit Transport, and 10% Non-Transport was assumed. Then a variation was considered in which the composition was 30% New Transport, 50% Retrofit Transport, and 20% Non-Transport – overall a less-equipped mixture of aircraft. Table 38 shows the relative collision rate based on the effects of situational awareness and alerting in each NextGen environment for each fleet mixture. The older fleet increased the collision rate in the NextGen 2 environment, where Retrofit Transport and Non-Transport were relatively less equipped. Otherwise, there was no difference because alerts were available, and 100% effective, for all three classes.

**Table 38. Collision Rate Relative to Baseline in Each NextGen Environment as a Function of Fleet Composition for Intersecting Arrivals Scenario**

| | Baseline Fleet | Older Fleet |
|---|---|---|
| **NextGen 1** | 100.0% | 100.0% |
| **NextGen 2** | 24.5% | 41.4 % |
| **NextGen 3** | 0.0% | 0.0% |
| **NextGen 4** | 0.0% | 0.0% |

## 6.6 Scenario 5: RNAV / RNP Approach

### 6.6.1 Overview

Figure 37 shows a diagram of the parallel RNAV / RNP approach scenario which was described in Section 4.6.3. In this scenario a better-equipped aircraft, with RNP of 0.3 nm or better, approached on a short trajectory, while a lesser-equipped aircraft, with RNP of 1.0 nm or worse, approached on a longer outside trajectory. The two aircraft's paths merged at a point just short of final approach. The intent was that the aircraft must maintain lateral separation while their paths were separate, and they should have crossed the merge point with sufficient longitudinal separation (corresponding to a sufficiently long time interval between when each aircraft crosses the merge point).

In operation this scenario would be used with a continuous stream of aircraft on both trajectories, merging to land on a common runway. Just two aircraft were modeled here, with the idea that the alerting system would be applied to each aircraft.

It was assumed that only the aircraft following the outer track could successfully respond to an alert. The inner aircraft was "boxed in" by the outer aircraft and had no feasible route by which to avoid a conflict, other than by landing as planned. The outer aircraft, on the other hand, could break off away from the inner aircraft.

This scenario differed from the previous scenarios in two important ways. First, the concept of collision risk was replaced with loss-of-separation risk, as it would be difficult to construct a blunder scenario leading to a collision. Loss of separation may trigger a time-consuming correction such as a missed approach, and in a congested airspace an avoidance maneuver could lead to conflicts with other aircraft.

Second, this scenario differed in the degree of information-sharing required and the complexity of assumptions regarding each aircraft's behavior. The alerting system must know the trajectories that have been assigned to the two aircraft. It was assumed that it would not be feasible to provide such information to an on-board system. Given that the aircraft following the outside track was assumed to have lesser equipage, it was not reasonable to assume that it would be able to receive a planned trajectory for the other aircraft. The better-equipped inner aircraft would likely have such a capability, but as noted above it did not have a feasible route to escape from a conflict.

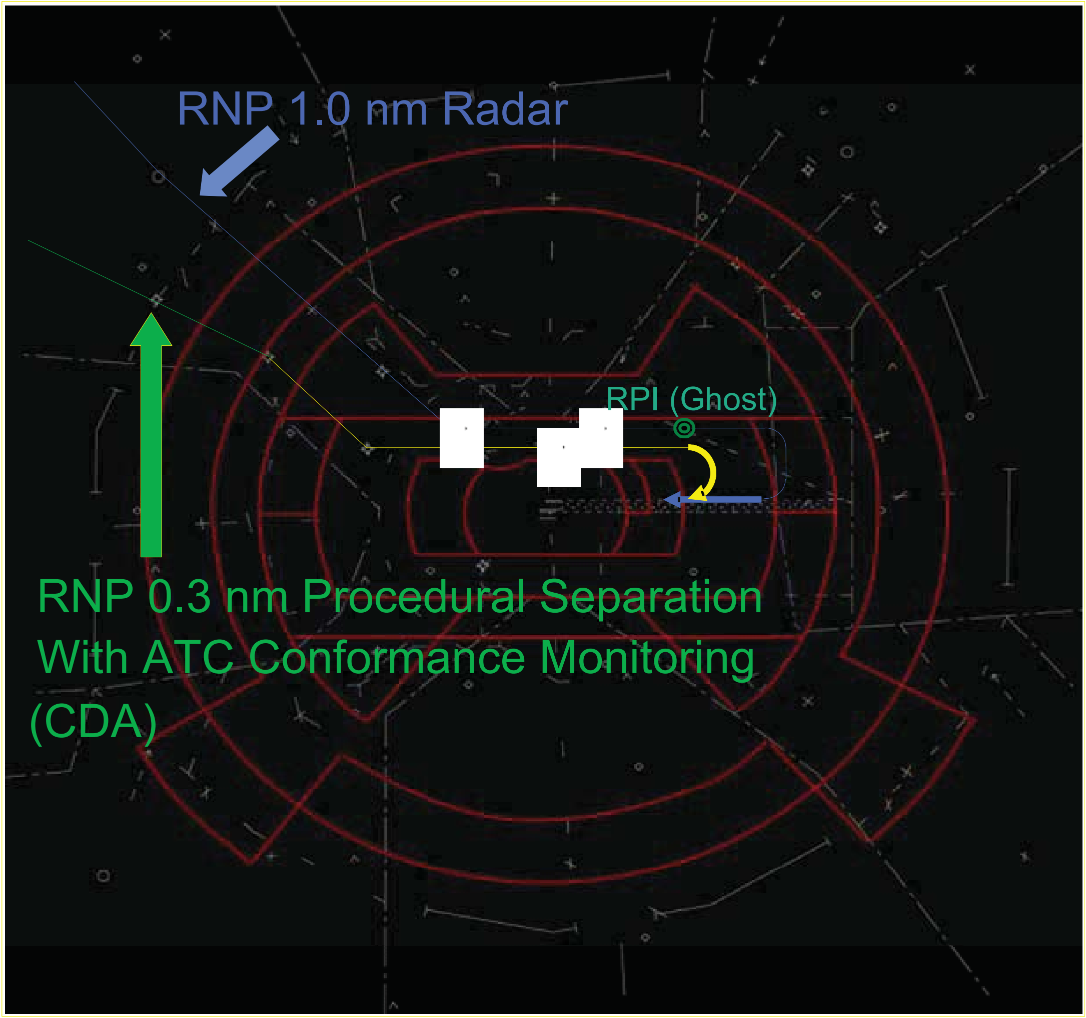



**Figure 37. RNAV / RNP Approach Scenario**

Therefore, it was assumed that only a ground-based alerting system was feasible. This system would receive the planned trajectories from the controller who issued clearance. That controller would monitor the aircraft for conformance with the plan, issuing speed adjustments as necessary. The alerting system served as a back-up for the controller. Note that in practice the design of the alerting system would be highly intertwined with the design of the controller's planning and guidance system.

Because on-board alerting was probably not feasible in this scenario, only NextGen environments 1 and 4 were considered. NextGen 1 was the baseline, and NextGen 4 showed the effect of the ground-based alerting system.

This scenario was also insensitive to the type or class of each aircraft, as each class has the same equipage, and the scenario did not depend on aircraft size parameters.

In the model, only the longitudinal position of the aircraft was considered and longitudinal conflicts were assessed. It was assumed that lateral separation was provided by a separate alerting function.

### 6.6.2 Scenario Model

Aircraft trajectories were modeled as straight-line paths with a semi-circular turn to the final landing approach. When the aircraft was on final, its speed was constant, but as it neared final approach it slowed gradually to the final approach speed. This was modeled as a constant deceleration. The merge point between the two trajectories was 1 nm before the beginning of final approach.

It was assumed that controllers were aiming for 60 seconds between the times when the two aircraft cross the merge point. A separation of 55 seconds or greater was considered acceptable. That is, alerts in encounters where the true spacing is 55 seconds or greater were considered nuisance alerts. "Loss of separation" was defined as occurring when the temporal spacing was 50 seconds or less. If it was between 50 and 55 seconds, no loss of separation had occurred, but an alert was not considered to be a nuisance. The scenario results were not sensitive to the absolute level of these temporal spacing thresholds, but only to the difference between them (5 seconds in this case).

Either aircraft could cross the merge point first; in the ensembles, half of the encounters had the inner aircraft crossing first and half had the outer aircraft crossing first.

Figure 38 shows the position and speed of the two aircraft as a function of time in a representative encounter. In this example, the outer aircraft crossed the merge point 56 seconds after the inner aircraft.

### 6.6.3 Loss-of-Separation Risk with and without an Alert

As discussed above, the risk of loss of separation was examined, rather than the risk of collision. Loss of separation occurred if the temporal spacing at the merge point was less than 50 seconds. If an alert was issued (to the outer aircraft only), it was assumed that the outer aircraft first attempted to adjust speed to restore acceptable spacing. It was also assumed that a speed change of up to 2.5% is possible. (This corresponds to a 5-knot speed adjustment at a typical speed of 200 knots.) The speed change happened after the alert was issued and a random response time has passed. If the speed change provided spacing better than 50 seconds at the merge point, the alert prevented loss of separation. Otherwise, the conflict was not resolved. It was likely in this case that the controller would have to order a more extreme evasive maneuver.

### 6.6.4 Projected Times and Margins

The time when each aircraft would cross the merge point was projected. The difference between these two times was the projected temporal spacing at the merge. Figure 39 shows an example of the evolution of this projected time margin as the scenario progressed.

When projecting crossing times, an uncertainty was applied to account for the degree to which the aircraft's path deviated from the nominal trajectory. The aircraft tended to "wobble" around the nominal trajectory due to random events such as gusts of wind. These wobbles increased the effective path length and hence the time required to traverse a route. It was assumed that the well-equipped inner aircraft (with RNP 0.3) followed an uncertain path and the relative uncertainty was 0.5%. The outer aircraft (with RNP 1.0) deviated to a greater degree, resulting in a greater uncertainty of 1.25%.

### 6.6.5 Alerting Algorithm

The alerting algorithm compared the projected temporal separation to two thresholds. First, to prevent nuisance alerts, the projected separation must be less than 55 seconds, minus 4 times the uncertainty. Second, to result in a significant risk of loss of separation, it must be less than 50 seconds, plus 4 times the uncertainty.

It was also required that the outer aircraft was within 4 minutes of the merge point, and had not already passed it.

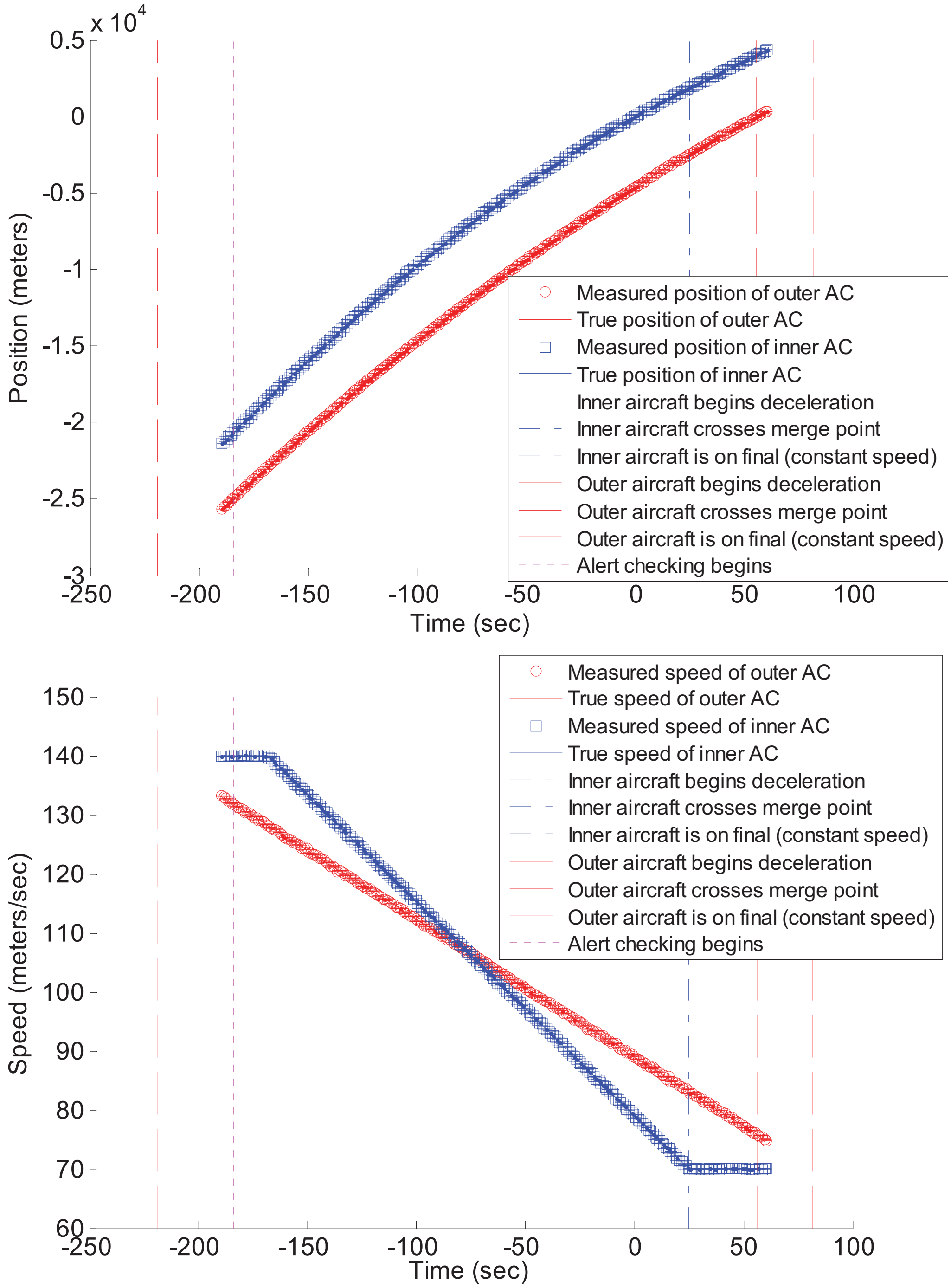



**Figure 38. Position (Top) and Speed (Bottom) of the Two Aircraft in the RNAV / RNP Approach Scenario**

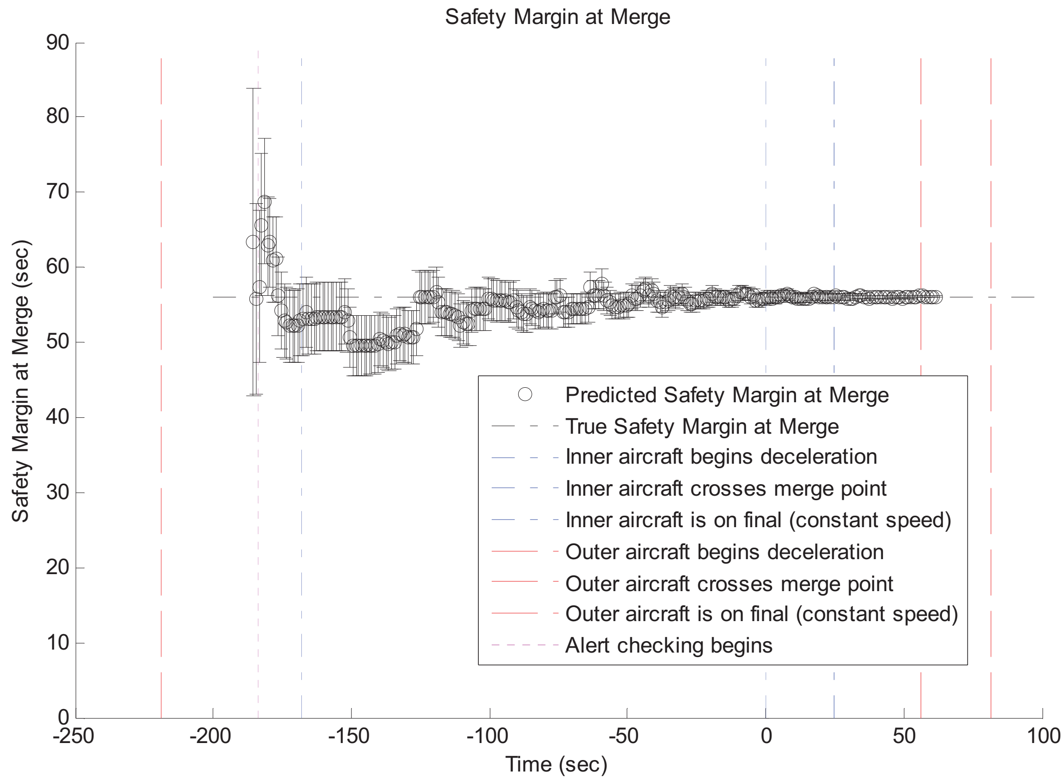



**Figure 39. Projected Time Margin at Merge Point, as a Function of Time when Projection Occurred**

### 6.6.6 Nuisance Alert Rate

The nuisance alert rate in an ensemble of encounters taken to represent normal operations was evaluated. In this ensemble, the time margin at the merge point ranged from 55 to 65 seconds. The most likely value was 60 seconds.

An ensemble of 400,000 encounters was evaluated. Of these, 71 encounters generated an alert, giving a nuisance alert rate of $(1.8 \pm 0.4)\text{x}10^{-4}$.

### 6.6.7 Alert Effectiveness

The performance of the alerting system depended critically on 3 parameters: the time at which the alert system began checking for a potential conflict, the relative uncertainty in distances due to deviations from the ideal trajectory, and the relative change in speed that was feasible in response to an alert. If the relative speed change was significantly greater than the relative distance uncertainty, an alert always came with enough time to perform a speed adjustment. The only possible failure in this case came when the adjustment needed to begin before the alerting system had begun checking for conflicts.

The alerting system responded effectively to minor blunders, where the true temporal spacing was just short of 50 seconds. For more extreme blunders, it was ineffective. This can be seen in Figure 40, which shows the risk of loss of separation as a function of the temporal spacing. Adjusting the scenario parameters shifted the point at which the alerting system became ineffective. For example, if a greater speed adjustment was possible in response to an alert, blunders of greater magnitude could be corrected.

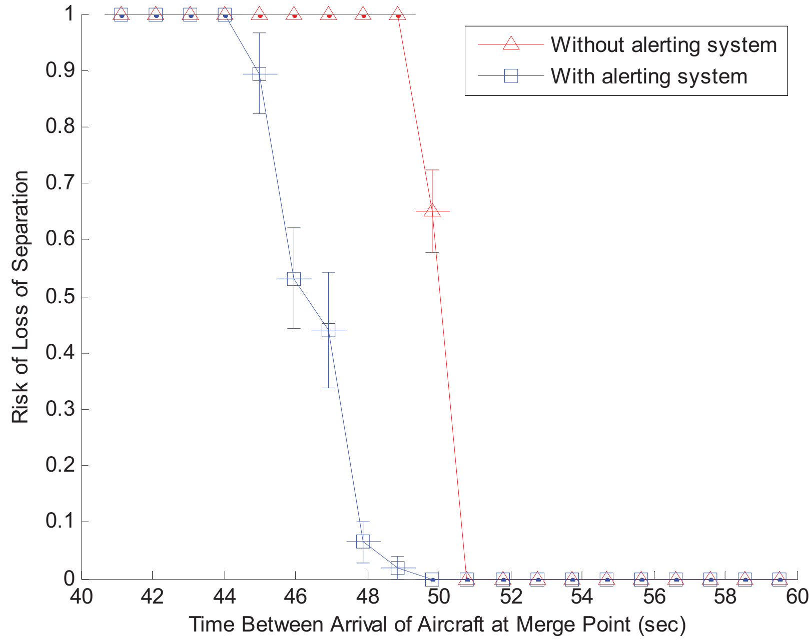



**Figure 40. Risk of Loss of Separation as a Function of the Time Margin between the Two Aircraft at the Merge Point**

Alert effectiveness was modeled using a blunder ensemble in which a merge time margin as low as 40 seconds, and as high as 60 seconds, was possible. The distribution of the merge time margin within the blunder ensemble is shown in Figure 41.

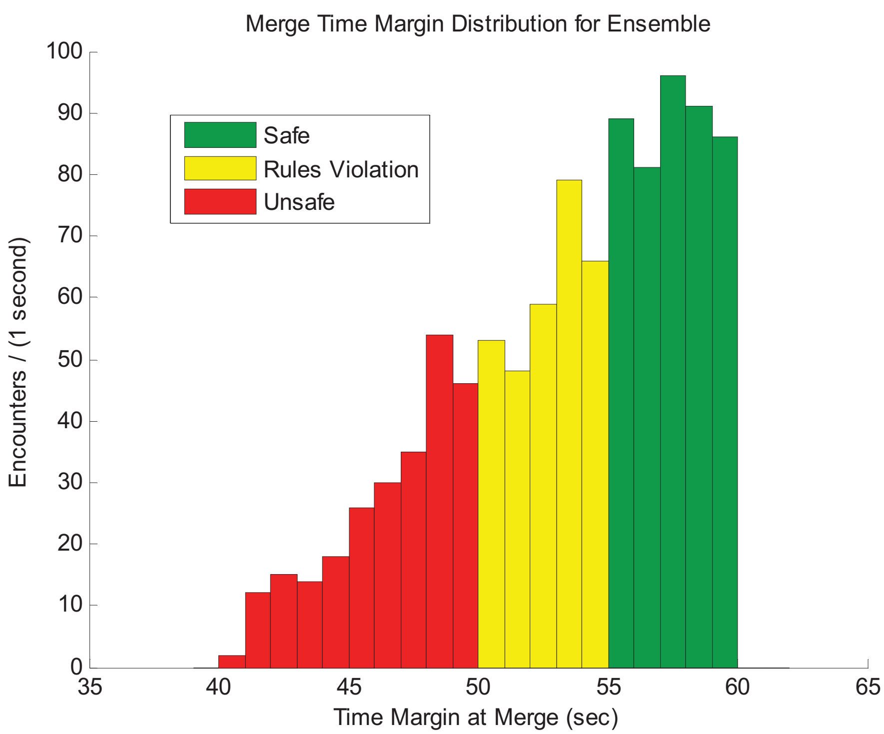



**Figure 41. Merge Time Margin Distribution in Blunder Ensemble**

#### 6.6.7.1 Dependence on Response time

It was assumed that the median pilot response time was 5 seconds. As in the previous scenario, the dependence on response time was evaluated by doubling and halving it. Table 39 shows the fraction of blunder encounters corrected as response time varied. Modest dependence on response time was found.

**Table 39. Fraction of Blunder Encounters Corrected by Alerting as a Function of Response time**

| | Response times x1/2 | Baseline | Response times x2 |
|---|---|---|---|
| Ground-Based Alert to Outer Aircraft | 61.3 ± 2.2 % | 59.4 ± 2.4 % | 55.2 ± 2.8 % |

#### 6.6.7.2 Dependence on Position Measurement Precision

A one-sigma position measurement accuracy of 5m was assumed. To explore the sensitivity of alert effectiveness to this parameter, new ensembles with accuracies of 2.5m and 10m were generated. Table 40 shows the fraction of blunder encounters corrected as measurement precision varied. There was no detectable effect; even a 10 meter uncertainty was insignificant compared to the other uncertainties in this scenario.

**Table 40. Fraction of Blunder Encounters Corrected by Alerting as a Function of Position Measurement Precision**

| | 2.5m Precision | 5m Precision | 10m Precision |
|---|---|---|---|
| Ground-Based Alert to Outer Aircraft | 61.5 ± 3.4 % | 59.4 ± 2.4 % | 59.8 ± 2.0 % |

#### 6.6.7.3 Dependence on ADS-B Velocity Measurement

The alerting algorithm was assumed to have access to an independent ADS-B measurement of velocity, rather than being limited to a velocity estimated from position measurements. The assumed accuracy of this measurement, either 0.03 m/s or 0.10 m/s according to the equipage model described in Section 6.1.3, was much better than the accuracy for velocity derived from smoothing recent position measurements. To explore the sensitivity of alert effectiveness to the availability of this measurement, alert effectiveness was evaluated with and without it. Table 41 shows the results. The ADS-B velocity measurement did have a significant effect.

**Table 41. Fraction of Blunder Encounters Corrected by Alerting With and Without ADS-B Velocity Measurement**

| | With ADS-B Velocity | Without ADS-B Velocity |
|---|---|---|
| Ground-Based Alert to Outer Aircraft | 59.4 ± 2.4 % | 38.4 ± 2.9 % |

#### 6.6.7.4 Dependence on Track Deviation Uncertainty

It was assumed that there was a 1.25% uncertainty in distance to the merge point due to deviations of the outer aircraft's true path from the ideal path. Two other values for this parameter, 0.75% and 2.5%, were tested. Table 42 shows the results; alert effectiveness depended strongly on this uncertainty.

**Table 42. Fraction of Blunder Encounters Corrected by Alerting as a Function of Track Deviation Uncertainty**

| | 0.75% | 1.25% | 2.5% |
|---|---|---|---|
| Ground-Based Alert to Outer Aircraft | 77.2 ± 1.9 % | 59.4 ± 2.4 % | 25.9 ± 2.7 % |

#### 6.6.7.5 Dependence on Relative Speed Change in Response to an Alert

It was assumed that upon receiving an alert, the outer aircraft could adjust speed by up to 2.5%. Two other values for this upper limit were tested, 1.25% and 5%. Table 43 shows the results. Alerting was much more effective when the aircraft performed a greater speed adjustment in response.

**Table 43. Fraction of Blunder Encounters Corrected by Alerting as a Function of Maximum Relative Speed Adjustment**

| | 1.25% | 2.5% | 5% |
|---|---|---|---|
| Ground-Based Alert to Outer Aircraft | 25.3 ± 2.7 % | 59.4 ± 2.4 % | 99.2 ± 0.5 % |

#### 6.6.7.6 Dependence on Time at which Conflict Checking Begins

It was assumed that the alerting system began checking for conflicts 4 minutes before the outer aircraft crossed the merge point. Two other values for this parameter were tested, 3 and 5 minutes. Table 44 shows the results. Alert effectiveness was fairly insensitive to this parameter. Typically an alert was not issued until the outer aircraft was within 3 minutes, so alert checking before that time had little effect.

**Table 44. Fraction of Blunder Encounters Corrected by Alerting as a Function of Time When Conflict Checking Begins**

| | 3 Minutes Prior | 4 Minutes Prior | 5 Minutes Prior |
|---|---|---|---|
| Ground-Based Alert to Outer Aircraft | 59.6 ± 2.2 % | 59.4 ± 2.4 % | 60.7 ± 1.9 % |

### 6.6.8 Comparison of NextGen Environments

With the default parameter values, it was found that the alerting system successfully corrected 59.4 ± 2.4 % of blunder encounters, meaning that 40.6% remain unresolved. Since only a ground-based system was tested, only the NextGen 1 and NextGen 4 environments were evaluated. In these environments, there was no difference in capabilities between aircraft classes. Therefore, performance in the NextGen 4 environment is described by the fraction of blunder encounters that remain unresolved in the default case (see Figure 42). As was seen above, this result was very sensitive to the assumed parameter values.

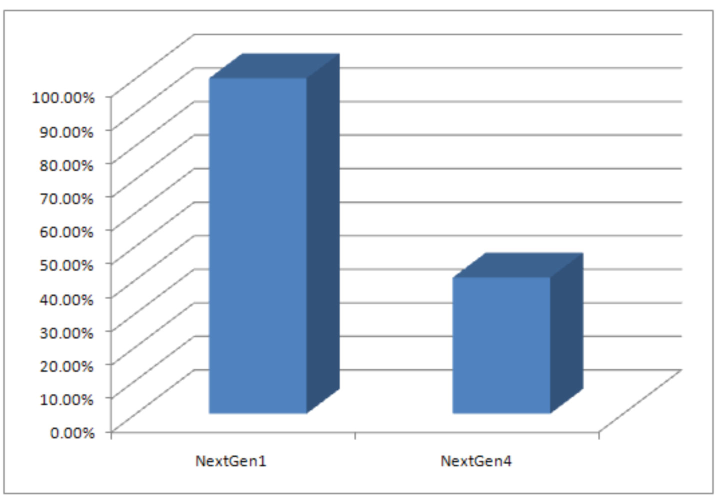



**Figure 42. Relative Collision Rates in NextGen 1 & 4 Environments, Relative to the Baseline (NextGen1) for RNAV / RNP Approach Scenario**

#### 6.6.8.1 Dependence on Fleet Composition

This scenario was insensitive to the class of each aircraft, and so it was insensitive to fleet composition.

# 7. Conclusions and Recommendations

The major conclusions of the modeling analysis are listed below.

Developing a quantitative analytical model for overall CD&R effectiveness in a future environment that addresses variations in surveillance quality, CD&R equipage, encounter parameters, and flight crew response time is challenging, but feasible.

The assumption that CD&R performance is limited primarily by kinematic state estimation and prediction rather than correctly classifying the encounter is important to the study conclusions. This assumption can be assured by the provision of appropriate air-ground data links for information on critical operational transitions, particularly intended runway, acceleration, and turns.

CD&R effectiveness should be modeled against a representative ensemble of encounters, rather than a small number of point scenarios, because the chance of successful response may depend critically on the time at which an error is made. Systematic or random (Monte Carlo) variation of the relative timing of encounters is essential to assess effectiveness.

The size of the margin between an acceptable operation and an encounter with collision risk is critical to the ability to achieve the desired nuisance alert rate while maintaining safety. Low nuisance alert rates are achievable under the assumption that occasional alerts for procedural violations of those safety margins are acceptable (i.e., not considered nuisance alerts). If operational safety margins are not much larger than the uncertainty in the CD&R prediction, either compromised detection or high nuisance alerts are inevitable. Therefore, if new NextGen procedures assume reductions in these margins, the CD&R capabilities assumed might not be achievable.

By expressing alert thresholds as functions of the uncertainties on decision variables, an alerting system that automatically adapts to the precision of surveillance and prediction can be created. Using separate thresholds to test for rules compliance and risk of collision or incursion, this system can be designed to keep nuisance alert rates sufficiently low while achieving as much safety benefit as the precision allows.

In the scenarios studied, operational rules provided safety margins that, in general, were large enough that the alert system could discriminate cleanly between high-risk encounters and those that comply with operational rules. Intermediate encounters, where a rule was violated but risk remained low, separated these extreme cases. Improved measurement precision typically had a modest effect on the alert rate in high-risk encounters, but allowed for a reduction in the alert rate on the intermediate encounters. This may allow for a reduction in the margins afforded by operational rules, with no loss of safety.

GPS-derived ADS-B velocity should be used in CD&R systems if it is as accurate as promised, but will only change alert effectiveness significantly where the margin between acceptable and unsafe behavior is relatively small and dependent on velocity measurement. In particular, it was found that using this measurement improved safety in the overtaking-taxi scenario, but not in the runway crossing, intersecting arrivals, or arriver following lander scenarios. However, the improved precision of this measurement did reduce the alert rates in encounters where an operational rule was violated but there was no significant collision risk.

The combination of object size uncertainty and residual error in ADS-B position in a multipath environment limits the ability to detect low-speed and static conflict situations (such as stationary targets slightly over the hold line.) However, if reasonable position margins are maintained, the collision risk from undetected violations of this type is small. Specifically, typical runway hold lines are 175 feet (53 m) from the runway edge, and collision risk should be considered high if an object comes within 10 m of the edge (with the risk becoming a function of the wingspan and flight technical error of the aircraft using the runway), giving an effective position margin of approximately 40 m between a correct and safe

position and a highly dangerous position for a stationary aircraft waiting to cross. Therefore, if residual size uncertainty and multipath result in reported position error that only rarely exceeds a fraction of this margin (for example, greater than 20 m in fewer than $10^{-5}$ of operations), the risk of undetected violations is small even if the threshold for alerting requires a reported position well past the hold line. The risk could be much greater at smaller or older airports with hold lines closer to the runway, although the dimensions of the runway and the aircraft using them must be considered to determine the actual risk.

Often the largest contribution to the uncertainty in predictions of future state is the assumed behavior of an aircraft after an operational transition (for example, how hard an arriver will brake after landing). When these uncertainties dominate, improvements in surveillance precision offer no benefit. To the extent that future behavior can be predicted more precisely, the alerting system may become more effective.

The results of perturbation analysis, which quantified the top-level performance impact of changes to key parameters such as median response time and surveillance position error, showed that the analytical model developed could be useful in making technology investment decisions.

Based on the simple models used for the benefits of passive situation awareness (provided by a CDTI), there is a substantial difference in overall safety capability between assumed NextGen environments. Under these models, investing in either comprehensive aircraft-based alerting or a ground-based alerting system would reduce the collision risk by multiple orders of magnitude compared to NextGen relying primarily on situation awareness. The degree to which initial lapses will be prevented by improved situation awareness is unknown. This factor, combined with increased demands in the NextGen environment, will determine whether the assumed NextGen baseline is significantly safer than current operations.

The assumed situational awareness benefit of cockpit displays such as CDTI strongly impacts the difference in safety between NextGen environments. Further research is needed to measure the extent to which these technologies help pilots to avoid or recover from lapses.

In scenarios requiring a prompt evasive maneuver to resolve a conflict, ground-based alerting is less effective due to the latency in communication between the aircraft and the alerting system. However, if a significant fraction of aircraft does not equip an on-board system, a ground-based system that issues alerts to all aircraft offers superior safety. Also, in some scenarios, the ground-based system may be able to coordinate alerts and resolution advisories among multiple aircraft to a degree that on-board systems cannot.

The sometimes-critical dependence of the conflict encounter outcome on flight crew response time demonstrates the need to consider the combined effect of situation awareness, workload, indications, and multi-level alerts on outcomes, and to validate the response time models assumed for the study.

The modeled safety benefits of CD&R depend on the ability to develop crew-vehicle interfaces that facilitate quick execution of the appropriate response, matching or exceeding the assumed response time distributions under realistic conditions. Integrating the capability for alerts with displays and indications that direct attention to the significant threats before they become acute should be a primary research focus.

Among the scenarios examined, performance depended most strongly on the level of equipage for the overtaking-taxi scenario, because taxiway CD&R was assumed to be provided only by high-end on-board or ground-based alerting systems. For runway collision hazards, partial equipage, as in the NextGen 2 and 3 environments, offered sufficient benefits because runway alerting was provided at a lower level of equipage.

## 7.1 Relation of Safety Modeling Results to CVI

The modeling analysis results for the Taxi Crossing / Arrival Runway and the Two Aircraft Taxiing Along Same Path scenarios demonstrated the potential criticality of pilot response to safety levels for NextGen TMA CD&R. The fact that three of five scenarios evaluated were sensitive to pilot response time suggests the following:

- All the hypothetical CVI and pilot performance issues described in Section 4.3 are important to analyze further.
- CVI and pilot performance issues may be more or less important depending on the operational scenario; cases where lead time for alerting are inherently shorter are the most critical to empirically analyze.
- CVI equipage intended to enhance SA and pilot response should improve pilot performance, but will not necessarily prevent the possibility that other pilot performance issues such as high workload or distractions will lead to unsafe CD&R outcomes.

The pilot response time effects found here need to be validated with empirical studies. Further, the relationships between operational situational factors, equipage, and human factors such as workload and distraction need to be analyzed more deeply to understand unintended as well as intended effects of improvements in CVI equipage.

Many of the other CVI issues described in Section 4.3 need to be explored with more in-depth modeling analyses as well as with empirical study. These include:

- The effects of pilot errors on safety levels; the analyses performed here only addressed response times.
- The effects of nuisance alerts, prescriptive commands, etc., on pilot response times and errors, especially when there is no visual information (zero-zero visibility) to confirm or disconfirm conflict information.
- The effects of strategic and predictive information pertaining to ownship and potential conflicts on CD&R safety levels.
- The effects of expected versus unexpected conflict events on pilot response times and errors.
- The trade-offs between better SA displays and the potential to overload pilots with too much information.

Other questions and issues for further research include:

1. Further research is needed to determine if the log normal curves for pilot response time used in the modeling effort accurately reflect the likelihood of response delays and errors under potentially higher workload conditions than are typical in today's environment.
2. An important research issue to address is pilot response to conflict situations when surveillance automation and various information sources add an automation management/awareness task to the primary task of assessing the conflict situation.
3. Research is needed to assure that the aggregate of new systems, equipage, and procedures don't overwhelm pilots with system interaction and training requirements.
4. Research is needed to address how specific tasks such as CD&R are performed in a full mission environment, especially if the conflict is completely unexpected.
5. A parametric study is needed to determine what distances should be designed into the path separations in order that the cross-track conflicts due to highly unlikely errors would be kept to an acceptable level of safety.

6. NextGen procedures may create new correlation patterns, for example, by reserving a runway or an approach corridor for a better-equipped class of aircraft. These interactions should be analyzed if the approach used in this study is extended to a more detailed analysis of safety capabilities. More specific definitions of assumed procedures, particularly those linked to equipage, and the assumed changes in the population of aircraft operations by class or type would be needed to perform such an analysis.

7. Further research is strongly recommended to validate the assumptions used in these scenarios. For example, the rate at which blunders are avoided due to improvements in general situation awareness strongly affects the incremental benefits to be derived from providing CD&R coupled with alerts.

8. Further research is recommended to determine whether there are "common mode" effects reducing the assumed benefit of independent conflict prevent actions. For example, if both A and B rely on a single source of information for a critical parameter such as B's position, and that source is incorrect, the probability of a correct response between the two is correlated, violating the assumption of independent performance.

9. Conflicting scenarios, in terms of potential blunder and deviations probabilities, need to be addressed empirically as well as with parametric analyses.

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## 9. Acronyms and Abbreviations

ACAS: Airborne Collision Avoidance System

ADS-B: Automatic Dependent Surveillance—Broadcast

ADS-R: Automatic Dependent Surveillance-Rebroadcast

AIA: Alarm Initiated Activity (model)

ANSP: Air Navigation Service Provider

ASDE-X: Airport Surface Detection Equipment—Model X

ASR: Airport Surveillance Radar

ATC: Air Traffic Control

ATCRB: Air Traffic Control Radar Beacon

ATM: Air Traffic Management

CCPC: Conditional Collision Prevention Capability

CDA: Continuous Descent Approaches

CDTI: Cockpit Display of Traffic Information

CD&R: Conflict Detection and Resolution

CVI: Crew Vehicle Interface

DGPS: Differential GPS

EFB: Electronic Flight Bags

EVO: Equivalent Visual Operations

EVS: Enhanced Visual System

FAA: Federal Aviation Administration

FAR: Federal Aviation Regulations

FIS-B: Flight Information Services –Broadcast

GA: General Aviation

GBAS: Ground-based Augmentation System

GNSS: Global Navigation Satellite System

GPS: Global Positioning System

HUD: Head Up Display

LCGS: Low-Cost Ground Surveillance

m: meters

MASPS: Minimum Aviation System Performance Standards

MFD: Multifunction Display

MLAT: Multi-lateration

NAC: Navigation Accuracy Category

NAS: National Airspace System

NextGen: Next Generation Air Transportation System

NIC: Navigation Integrity Category

NPRM: Notice of Proposed Rule Making

R&D: Research and Development

RAAS: Runway Awareness & Advisory System

RMS: Root Mean Square

RNAV: Area Navigation

RNP: Required Navigation Performance

RT: Response Time

RTA: Required Time of Arrival

RTCA: Radio Technical Commission for Aeronautics

RWSL: Runway Status Lights

SA: Situation Awareness

SMR: Surface Movement Radar

STBO: Surface Trajectory Based Operations

SURF: Surface

SURF IA: Surface Indications and Alerting

SVS: Synthetic Vision System

TBO: Trajectory Based Operations

TCAS: Traffic Alert and Collision Avoidance System

TIS-B: Traffic Information Services -Broadcast

TMA: Terminal Maneuvering Area

TRACON: Terminal Radar Control

UAT: Universal Access Transceiver

VFR: Visual Flight Rules

VOR: VHF Omnidirectional Range

WAM: wide area multi-lateration

| REPORT DOCUMENTATION PAGE | *Form Approved* *OMB No. 0704-0188* |
|---|---|



**1. REPORT DATE** *(DD-MM-YYYY)*
01- 04 - 2011

**2. REPORT TYPE**
Contractor Report

**3. DATES COVERED** *(From - To)*
September 2008-December 2009

**4. TITLE AND SUBTITLE**
Parametric Modeling of the Safety Effects of NextGen Terminal Maneuvering Area Conflict Scenarios

**5a. CONTRACT NUMBER**
NNLO6AA05B

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Rogers, William H.; Waldron, Timothy P.; Stroiney, Steven R.

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**
NNLO8AD71T

**5f. WORK UNIT NUMBER**
411931.02.73.07.01

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
NASA Langley Research Center
Hampton, VA 23681-2199

Honeywell International Inc.
1985 Douglas Drive North
Golden Valley, MN 55422

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Washington, DC 20546-0001

**10. SPONSOR/MONITOR'S ACRONYM(S)**
NASA

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
NASA/CR-2011-217082

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified - Unlimited
Subject Category 03
Availability: NASA CASI (443) 757-5802

**13. SUPPLEMENTARY NOTES**
Langley Technical Monitor: Denise R. Jones

**14. ABSTRACT**
The goal of this work was to analytically identify and quantify the issues, challenges, technical hurdles, and pilot-vehicle interface issues associated with conflict detection and resolution (CD&R)in emerging operational concepts for a NextGen terminal aneuvering area, including surface operations. To this end, the work entailed analytical and trade studies focused on modeling the achievable safety benefits of different CD&R strategies and concepts in the current and future airport environment. In addition, crew-vehicle interface and pilot performance enhancements and potential issues were analyzed based on review of envisioned NextGen operations, expected equipage advances, and human factors expertise. The results of perturbation analysis, which quantify the high-level performance impact of changes to key parameters such as median response time and surveillance position error, show that the analytical model developed could be useful in making technology investment decisions.

**15. SUBJECT TERMS**
Conflict Detection, Resolution, Modeling Analysis, Terminal Maneuvering, NextGen, Aviation Safety

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | STI Help Desk (email: help@sti.nasa.gov) |
| | | | | | 19b. TELEPHONE NUMBER *(Include area code)* |
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**Standard Form 298** (Rev. 8-98)
Prescribed by ANSI Std. Z39.18